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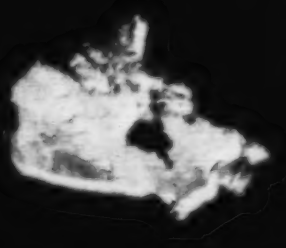

Optimization of gluing, lay-up and pressing for mountain pine beetle plywood

Brad Wang[1], Chunping Dai[1] and Steve Wharton[2]

Mountain Pine Beetle Initiative
Working Paper 2007-03

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Executive Summary

We investigated the possibility of increasing value recovery from mountain pine beetle (MPB)-attacked lodgepole pine (*Pinus contorta* Dougl.) logs by adjusting the plywood manufacturing process specifically for the beetle-killed resource. The project addressed veneer grading, gluing, panel lay-up and hot pressing, and was a follow up to an earlier study that demonstrated that, by segregating beetle-killed logs, the productivity and material recovery could be improved at the early stages of production through narrower veneer clipping width, more accurate moisture sorting and higher drying productivity (Wang and Dai 2004). Based on the comparative results between the beetle-wood veneer and non-affected control veneer from pilot plant tests and mill trials, this study found that the beetle-wood veneer is denser and stronger than the control veneer from a typical white wood mix (i.e. white spruce, lodgepole pine and subalpine fir). As long as manufacturing parameters are properly adjusted in drying, grading, gluing and hot-pressing, segregating MPB logs provides an opportunity to manufacture higher-stiffness laminated veneer lumber (LVL) and plywood products with superior wet and dry gluebond performance for such applications as wood I-joists, headers and beams, flooring, decking and concrete forming. This could further offset, to a large degree, the reduction in material recovery and some appearance-based plywood products in the Japanese market. As well, the practice of segregation will become more important for recovering the highest value as the mill supply of beetle-killed wood becomes greater than 25% of total mill log supply, with most of beetle-killed wood being grey-stage materials.

Plywood production was affected by beetle-killed logs as follows:

The beetle-wood veneer is lower in moisture content (MC), more brittle, and more difficult to handle. It also contains various degrees of blue stain. To increase material recovery and panel gluebond performance, veneer overdrying must be minimized. The machine vision technology currently used by some plywood/LVL mills cannot differentiate defects within the blue-stained area of the wood. To improve veneer visual sorting, the existing vision systems can be upgraded to mask the effect of blue stain or to segregate the blue-stained veneer from the non-stained veneer using a saturation color index etc. Compared to the control veneer, the beetle-wood veneer is higher not only in dry bonding performance but also in wet bonding performance, as measured by shear strength and percent wood failure. To increase the grade outturn, stress grading of the beetle-wood veneer should be based on modulus of elasticity (MOE) instead of ultrasonic propagation time (UPT). As well, the beetle-wood veneer is approximately 10% higher in average MOE and 20% higher in stress-grade outturn, which can translate into more than $1.5 million additional annual savings for the mill when processing 10% of beetle-killed logs. To achieve optimum gluebond performance and minimum manufacturing cost for beetle-wood plywood, glue spread can be kept at the same level as currently used by control plywood. However, the pressing time of five-ply beetle-wood plywood should be lengthened by about 10% compared to that used by five-ply control plywood. As well, the assembly time should be reduced to about 10 -15 min. Furthermore, five-ply plywood manufacturing trials and 13-ply LVL preliminary tests demonstrated that the MOE and modulus of rupture (MOR) of beetle-wood plywood and LVL are about 15% and 20% higher than those of control plywood and LVL, respectively. As a result, the beetle-wood veneer is more suitable for making higher-stiffness LVL and specialty structural plywood products. By implementing this product strategy, the value recovery from the beetle-killed resource can be dramatically increased.

Keywords: mountain pine beetle, *Dendroctonus ponderosae*, blue-stained veneer, grading, gluing, layup, plywood manufacturing, laminated veneer lumber (LVL), value recovery

Résumé

Nous avons exploré la possibilité d'augmenter la récupération de la valeur des grumes de pins tordus *(Pinus contorta Douglas)* attaqués par le dendroctone du pin ponderosa en adaptant le procédé de fabrication du contreplaqué aux ressources tuées par ce ravageur. Le projet portait sur le classement des placages, l'encollage, l'assemblage des panneaux et le pressage à chaud, et faisait suite à une étude

précédente ayant démontré qu'en séparant les grumes attaquées par le dendroctone des grumes qui ne l'étaient pas, la productivité et la récupération du matériau pouvaient être améliorées dès les premières étapes de la production en massicotant plus finement les placages, en améliorant la précision du tri selon l'humidité des grumes et en améliorant la productivité du séchage (Wang et Dai, 2004). Cette étude, qui repose sur les résultats comparatifs d'essais en usine et en scierie sur les placages attaqués et non attaqués, montre que le placage obtenu à partir de pin attaqué par le dendroctone est plus dense et plus résistant que le placage témoin obtenu à partir du traditionnel mélange de bois blanc. Dès lors que les paramètres de fabrication sont correctement ajustés en ce qui concerne le séchage, le classement, l'encollage et le pressage à chaud, la séparation des grumes tuées par le dendroctone offre la possibilité de fabriquer des produits de bois en placage stratifié (LVL) plus rigides et de contreplaqué dont le joint en colle (humide ou sec) a un rendement supérieur et qui peuvent être utilisés pour des solives en I en bois, des poutres ou des chevêtres, des planchers, des platelages et le coffrage du béton. Cela peut compenser, dans une large mesure, la réduction de la récupération du matériau et l'apparition sur le marché japonais de certains produits esthétiques en contreplaqué. Cette pratique de ségrégation deviendra également très importante pour récupérer la plus grande valeur lorsque l'approvisionnement de la scierie en bois tué par le dendroctone (majoritairement au stade gris) dépassera le quart de l'approvisionnement total en grumes de la scierie.

La production de contreplaqué a été touchée par les grumes tuées par le dendroctone de la façon suivante :

Les placages attaqués par le dendroctone sont plus secs, plus cassants et plus difficiles à manipuler. Ils présentent également différents degrés de taches bleues. Si on veut augmenter la récupération du matériau et le rendement du joint en colle des panneaux, il faut minimiser le séchage excessif des placages. La technologie de vision artificielle utilisée présentement par certaines scieries de contreplaqué ou de LVL ne peut pas différencier les défauts présents dans les zones bleuies du bois. Afin d'améliorer le tri visuel des placages, les systèmes de vision existants peuvent être modifiés de façon à masquer l'effet de la tache bleue ou à séparer les placages tachés de ceux qui ne le sont pas, en utilisant un indice de couleur de saturation. Comparés aux placages témoins, les placages attaqués par le dendroctone ont une plus grande résistance lorsqu'ils sont secs mais aussi lorsqu'ils sont humides, selon les résultats obtenus après avoir mesuré leur résistance au cisaillement et la proportion de ruptures dans le bois. Ces placages ont également un module d'élasticité de 10 p. 100 plus élevé en moyenne et une production dont la qualité de résistance aux contraintes est de 20 p. 100 plus élevée, ce qui peut se traduire par des économies annuelles de 1,5 millions de dollars supplémentaires pour une scierie qui traite 10 p. 100 de grumes tuées par le dendroctone. Pour que le rendement du joint de colle soit optimal et que les coûts de fabrication du contreplaqué attaqué par le dendoctrone soient minimaux, l'encollage peut être maintenu au même niveau que ce qui est actuellement utilisé avec le contreplaqué témoin. Cependant, le temps de pressage du contreplaqué à 5 épaisseurs préparé avec du bois attaqué par le dendroctone devrait être allongé de 10 p. 100 par rapport au contreplaqué à 5 épaisseurs témoin. Le temps d'assemblage devrait aussi être réduit de 10 à 15 minutes, en maintenant la température des placages aussi basse que possible. En outre, les essais de fabrication de contreplaqué à 5 épaisseurs et les essais préliminaires de LVL à 13 épaisseurs ont montré que le module d'élasticité ou la résistance à la flexion du contreplaqué et du LVL obtenus à partir de bois attaqué par le dendroctone sont respectivement de 15 p. 100 et de 20 p. 100 plus élevés que ceux du contreplaqué et du LVL témoins. Les placages obtenus à partir de bois attaqué par le dendroctone sont donc mieux adaptés à la fabrication du LVL plus rigide et de produits en contreplaqué spécialement conçus pour la construction. Avec cette stratégie, la récupération de la valeur d'une ressource tuée par le dendroctone peut être considérablement augmentée.

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1 Objectives

The overall objective of this project was to determine the impact of using mountain pine beetle (MPB)-attacked wood on plywood manufacturing processes and to implement the optimum processing parameters in mill production in order to increase value recovery and productivity.

The specific objectives of this project were to investigate and quantify the:

- effect of beetle-wood veneer on veneer visual and stress grading;
- effect of beetle-wood veneer on gluing, panel lay-up and gluebond performance;
- effect of beetle-wood veneer on the plywood hot-pressing process and resulting panel quality, stiffness and strength; and
- costs and benefits of adjusting manufacturing processes in a mill trial that transfers the technology.

2 Introduction

Lodgepole pine (*Pinus contorta* Dougl.) is one of the most common softwood species used for plywood and laminated veneer lumber (LVL) manufacturing in western Canada. The large outbreak of mountain pine beetle (MPB) has changed the nature of the resource available to veneer producers in B. C. Because the beetle has preferentially attacked the larger trees, the infestation has resulted in an increased percentage of larger diameter, but drier, checked and stained logs entering plywood/LVL mills.

This project follows directly from the results of an earlier Mountain Pine Beetle Initiative sponsored project completed by the same investigators (Wang and Dai 2004). The 2004 study investigated manufacturing process adjustments at the early stages of production: log conditioning and peeling, through to veneer drying and recommended process changes to optimize manufacturing practices for the altered resource. Sorting and processing the beetle-wood logs separately from normal whitewood logs proved cost effective for the participating mill once the percentage of those killed by beetle exceeded about 10% of the log supply. The adjustments resulted in increased productivity and material recovery at the participating mill through narrower veneer clipping width, more accurate moisture sorting and higher drying productivity. However, product value recovery from the beetle-killed logs remained less than that from normal logs because of about 8% lower in overall material recovery from veneer peeling, clipping, drying to composing. The present study is designed to investigate whether it is possible to increase the value recovery from the beetle-killed log supply by optimizing for the rest of the manufacturing process (veneer grading, gluing, panel lay up, and hot pressing) to the beetle-killed resource.

In the 2004 study the impact of using beetle-wood logs on veneer recovery was quantified. Optimum manufacturing parameters were determined through laboratory tests, pilot-plant tests and mill trials. The results showed that post-beetle attack wood is drastically different from normal wood in terms of moisture content (MC), veneer processing characteristics, log conditioning, veneer peeling, drying and optical visual scanning. Following the success of the first study, this research aims to investigate the effect of the mountain pine beetle-killed wood on veneer visual and stress grading and to establish the optimum manufacturing parameters from veneer gluing, panel lay-up to hot-pressing. The mill trial was conducted at the same mill as the 2004 study to ensure that the impact on overall value recovery can be quantified.

In the plywood mill where this study was conducted, the typical plywood species mix is comprised of approximately 30% Douglas-fir containing about 15% western larch, 40% lodgepole pine containing about 25% of total volume beetle-killed wood, 20% white spruce and 10% subalpine fir. The typical white wood veneer production is a mixture of lodgepole pine, white spruce and subalpine fir, accounting for about 70% of total mill production. In the Canadian softwood plywood (CSP) industry, the typical white wood log mix is generally not sorted prior to making standard CSP plywood.

Compared to the control veneer, the beetle-wood veneer has stains, more checks, and is drier, rougher, more brittle, more permeable and has different surface chemistry. These characteristic changes can

affect veneer grading, veneer gluing and panel pressing through their impact on surface appearance, wettability, bondability, glue penetration, heat and mass transfer. To achieve target gluebond performance as measured by percent wood failure and shear strength for the final panel products, a higher glue spread level or a longer pressing time may be needed; or the glue formulation may need to be changed to avoid dry-out of the glueline. To address possible concerns in the marketplace, the plywood/LVL lay-up may need to be adjusted to use blue-stained veneer for crossbands or inner-plies. To maximize manufacturing productivity and material recovery, the effect of using the beetle-wood veneer on the hot pressing of plywood/LVL products and resulting panel quality, stiffness and strength must be investigated. Another important factor is the sheer volume of the beetle-wood veneer that a mill needs to handle.

Both pilot plant tests and mill trials were based on proven experimental methods previously established by Forintek that ensure that results are both scientifically valid and useful to the industry. The mill trial allowed a practical assessment of the processing adjustments to be determined in order to maximize the value recovery and minimize handling problems associated with the beetle-attacked wood. The outcome will help plywood/LVL mills further increase the productivity and value recovery from the beetle-wood logs and is expected to be promptly transferred to the industry for implementation in mill production.

3 Staff

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4 Materials and Methods

4.1 Pilot Plant Testing

For this study, one hundred and eighty (180) sheets (1.22 x 2.44 -m or 4 x 8 -feet) of dried beetle-wood veneer and one hundred and twenty (120) sheets (1.22 x 2.44 -m) of dried control white wood veneer were randomly selected from those peeled from segregated mountain pine beetle-killed lodgepole pine logs and typical control white wood mix logs, respectively. The veneer was 3.2 mm (1/8-inch) thick. To make the veneer samples representative, the sheets were sampled from different shifts throughout the day. Then they were delivered to Forintek's Composite Pilot Plant. These beetle-wood veneer sheets were peeled from the typical mixture of different stages of beetle-wood logs being received by the mill, comprising blue-stained sapwood veneer and non-stained heartwood veneer.

At Forintek's Composites Pilot Plant, each 1.22 x 2.44 -m veneer sheet was trimmed into two 1.22 x 1.22 -m (4 x 4 -feet) half sheets (Figure 1). Then two 81.3 x 40.6 -cm (32 x 16 -inch) and two 40.6 x 40.6 -cm (16 x 16 -inch) sub-sheets were further cut from each 1.22 x 1.22 -m sheet for plywood and LVL manufacture, as shown in Figure 2. In total, about 650 and 400 veneer sub-sheets in 81.3 x 40.6 -cm and about 500 and 300 veneer sub-sheets in 40.6 x 40.6 -cm were generated from the beetle-wood veneer and control veneer, respectively.

In addition, about five hundred 64 x 64 -mm (2.5 x 2.5 -inch) and eighty 30 x 30 -mm veneer pieces were randomly cut from the remainder of the beetle-wood veneer and control veneer, respectively, for image analysis and compression tests.

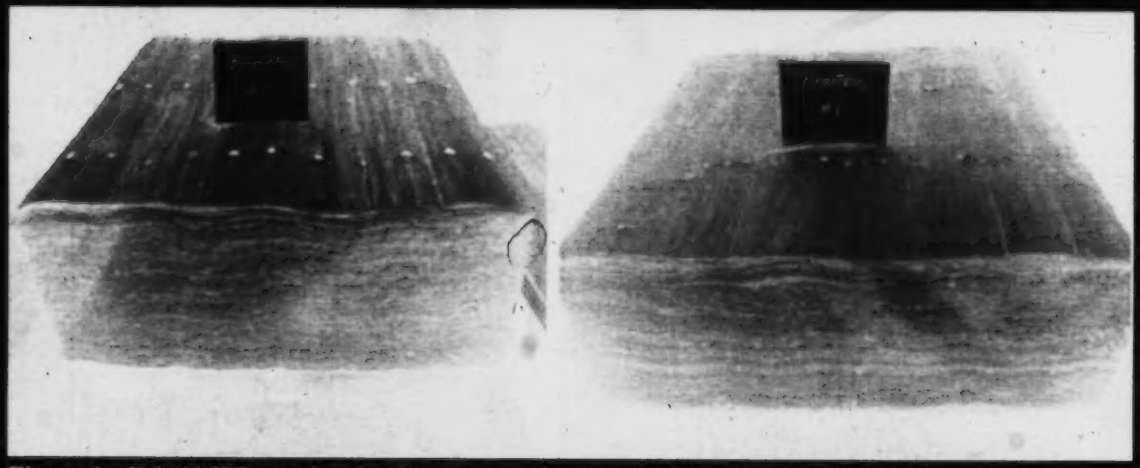


Figure 1: Dried MPB wood and control veneer sheets sampled from a plywood mill

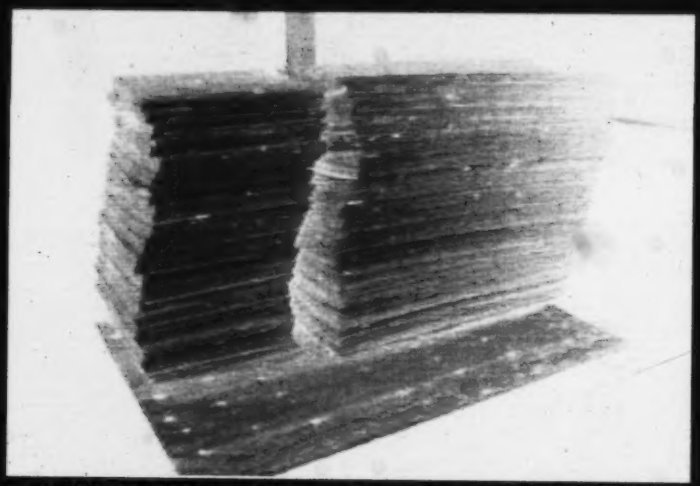


Figure 2: Veneer sheets cut for manufacturing plywood and LVL

4.1.1 Veneer Quality, Stress Grading and Visual Grading

4.1.1.1 Veneer Stress Grading

Veneer stress grading is commonly used for manufacturing structural LVL and specialty plywood panel products. As these are typically high value products, it was important to check that the grading methods are optimal for the beetle-killed resource. Currently, two methods are commonly used to sort veneers into stress grades: (1) sorting based on ultrasonic propagation time (UPT) or (2) sorting based on veneer MOE.

Thirty-six veneer sheets (81.3 x 40.6 -cm) were randomly selected from each of two categories: beetle-wood veneer (a mixture of blue-stained and non-stained heartwood veneer) and control veneer, respectively. They were then put into plastic bags to maintain the moisture condition until they were measured. The length, width, 9-point thickness and weight of each sheet were measured and the mean sheet density calculated. Veneer moisture content (MC) was checked and recorded. As shown in Figure 3, a portable Metriguard stress wave timer was used to measure stress wave time (equivalent to UPT). For this measurement, eleven (11) straight lines were drawn along the grain on the loose (lathe checked) side of each veneer sheet with a lateral separation of 38 mm (1.5 inches). The distance between the sending transducer and receiving transducer was 76.2 cm (30 inches). Based on the mean density and stress wave time of each veneer sheet, the dynamic veneer MOE was calculated. A t-test was conducted to compare whether there is a significant difference in veneer density, stress wave time and stiffness (or MOE) between the beetle-wood veneer and control veneer. The results help benchmark the characteristics and use of the beetle-wood veneer for structural plywood and LVL products.

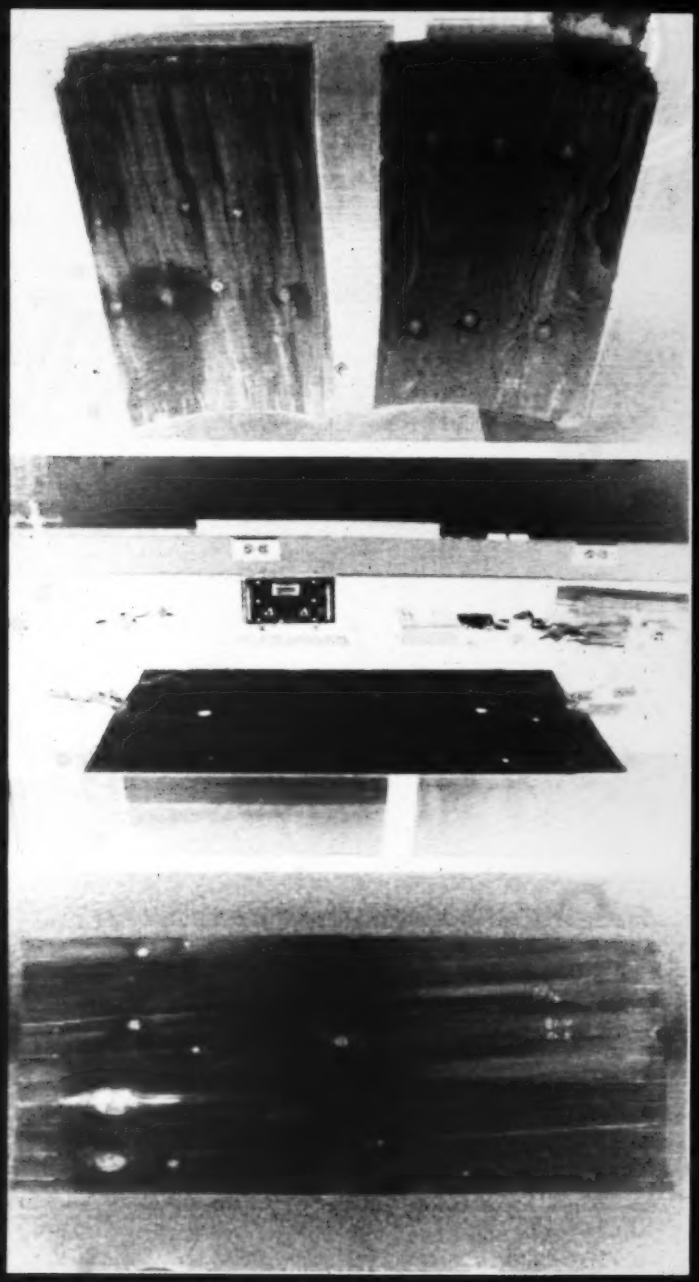


Figure 3: Stress wave testing of the beetle-wood veneer and control veneer

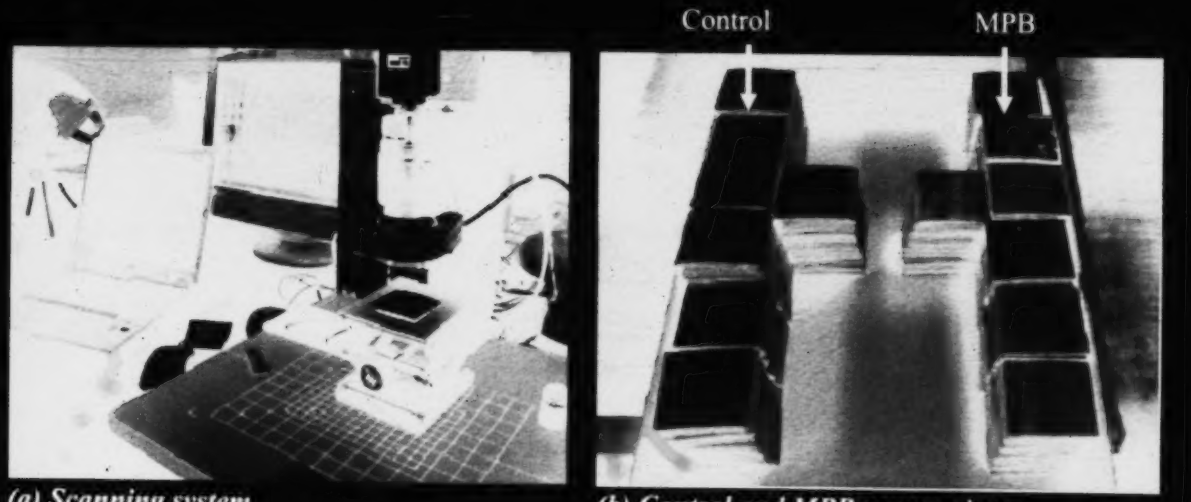
4.1.1.2 *Dry Veneer Quality*

Veneer thickness variation and roughness are the two important veneer quality criteria. For evaluating veneer thickness, the dry thickness data of 36 beetle-wood veneer sheets (81.3 x 40.6 -cm) and 36 control veneer sheets (81.3 x 40.6 -cm) from stress grading tests were used. In total, 324 data points were generated for the beetle-wood veneer and control veneer, respectively. Both within-sheet and between-sheet veneer thickness variations were analyzed. A t-test was conducted to compare whether there is a significant difference in the dry veneer thickness.

For measuring dry veneer roughness, forty 30 x 30 -mm pieces were randomly selected from the beetle-wood veneer and control veneer, respectively. A newly developed method for evaluating surface roughness and compressibility was used (Wang et al. 2006a and b). Through compression tests of small 30 x 30 -mm pieces, the minimum compression required for the veneer to achieve adequate contact with the smooth steel plate was identified for each veneer piece under a threshold load of 100 kg. This minimum compression obtained from the load-displacement curve of the compression test was found to be well correlated to the veneer surface quality (roughness). The difference in the minimum compression required (or roughness) between the beetle-wood veneer and control veneer was statistically analyzed using t-tests.

4.1.1.3 *Veneer Visual Grading*

Five hundred 63.5 x 63.5 -mm (2.5 x 2.5 -inch) beetle-wood veneer pieces (randomly cut from beetle-wood veneer) contained various levels of blue stain, knots, resin pockets and cracks. As shown in Figure 4, an image system developed at Forintek was used to determine the visual characteristics of the beetle-wood veneer, especially blue-stained veneer, and its effect on visual grading (Groves 2000). To perform optical scanning, 150 pieces were randomly selected from the 500 pieces cut for the beetle-wood veneer. As a control, 150 pieces were also randomly selected from the 500 pieces cut for the control veneer. One image (1 x 1 -cm area) each was taken from the blue-stained area of each beetle-wood veneer piece and central area of each control veneer piece, respectively. The average values of Red, Green and Blue (RGB) (from 0 to 255) and Hue (0 to 360°), Saturation (0 to 100%) and Luminance or Lightness (0 to 100%) in HSL color space of each image were extracted. The frequency distribution of Red, Green and Blue (RGB) values and Hue, Saturation and Luminance (HSL) indexes was then established for both MPB blue-stained veneer and control veneer.



(a) Scanning system ***(b) Control and MPB veneer pieces***

Figure 4: Systems for scanning MPB and control veneer pieces

4.1.2 *Effect of MPB Veneer on Gluing, Panel Lay-up, Shear Strength and Percent Wood Failure*

4.1.2.1 Veneer Transverse Permeability

The air permeability of wood has a remarkable effect on wood drying productivity and wood treatment efficiency. To date, comparative tests on air permeability of beetle-killed wood and control wood have been conducted by several authors (Oliveira et al. 2005; Woo et al. 2005). However, comparative tests of air permeability of the beetle-wood veneer and control veneer have not been done. In the case of veneer, lathe checks may have a more significant effect on veneer air permeability. During gluing and hot-pressing of veneer-based wood composites, the veneer transverse air permeability, rather than lateral permeability, determines the degree of glue penetration and diffusion of hot air and high temperature vapor from surface layers to the core at the stages of panel consolidation and curing, and the ease of their evaporation at the stage of degassing. The first inward air and vapor movement will mainly determine the rate of core temperature rise and hence efficiency of hot-pressing. During the later stage of pressing, the outward air and vapor movement will allow core gas pressure to release and determine whether defects such as blows or delamination can be suppressed. Further, the veneer transverse air permeability will influence the ease of post-treatment and degree of formaldehyde emission of panels in application.

Thirty 60 -mm round beetle-wood veneer disks and thirty (30) 60 -mm round control veneer disks were randomly cut from ten representative beetle-wood and control veneer sheets, respectively. Among the 30 disks of the beetle-wood veneer, half were blue-stained sapwood veneer and half were non-stained heartwood veneer. The air permeability of veneer was measured using a standard permeability measurement device, as shown in Figure 5. The *t*-tests were performed to identify whether there is a significant difference in transverse air permeability between the MPB blue-stained veneer, MPB non-stained veneer and control veneer.

Since the control veneer was the mixture of lodgepole pine, white spruce and subalpine fir, in order to determine the effect of blue stain on veneer air permeability, six representative lodgepole pine sapwood and heartwood veneer sheets were selected from the control veneer for tests. Ten 60 -mm round disks were randomly cut from each of sapwood and heartwood veneer sheet, respectively. To minimize the effect of lathe checks on air permeability, two-ply glued disk pairs were prepared for the MPB blue-stained veneer, MPB non-stained veneer and control lodgepole pine sapwood and heartwood veneer. The permeability measurements were then performed. The t-tests were further conducted to identify the difference in the air permeability.

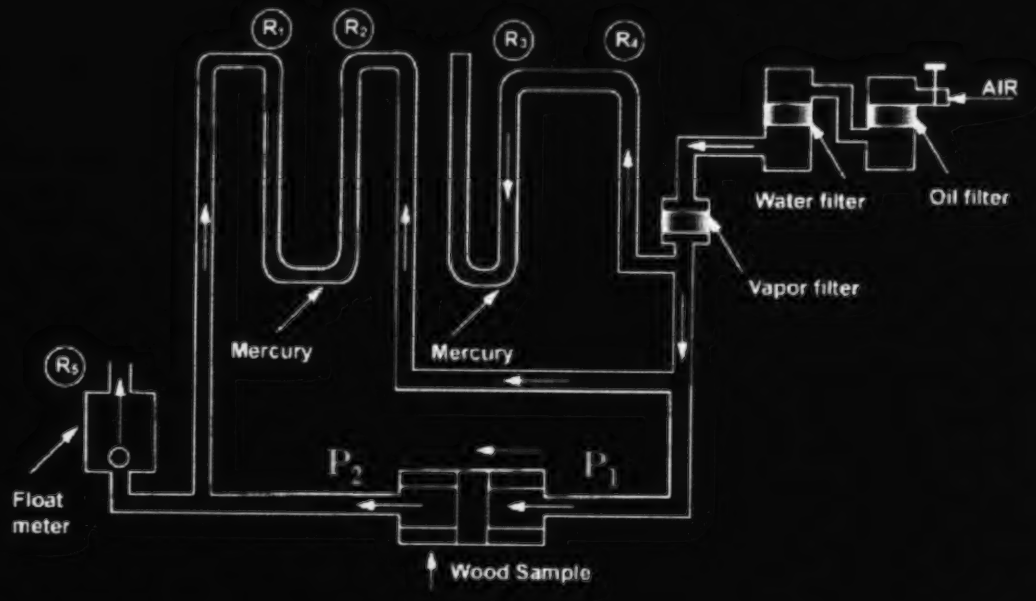


Figure 5: The measurement device for veneer transverse (radial) permeability

4.1.2.2 pH and Lap Shear Tests

As shown in Figure 6, the pH value of the blue-stained veneer and non-stained veneer was conducted using a pH indicator. From the color difference, it can be roughly determined if there is a significant difference in pH value between the blue-stained veneer and non-stained veneer.

Figure 6: Use of the pH indicator on blue-stained and non-stained veneer

For establishing optimum lay-up scheme, as shown in Figure 7, small pieces of veneer strips (100 x 20 - mm) were randomly cut for lap-shear tests: 200 each for the beetle-wood veneer and control veneer, respectively. Six lay-ups were considered, as shown in Table 1.

Table 1: Lap-shear tests

Lay-up type	Veneer type (X_1)	Construction (X_2)	Replicates
A	Blue-stained - blue-stained	Loose side to loose side	15
B	Blue-stained - blue-stained	Loose side to tight side	15
C	Blue-stained – control	Loose side to loose side	15
D	Blue-stained - control	Loose side to tight side	15
E	Control - control	Loose side to loose side	15
F	Control – control	Loose side to tight side	15

The Automated Bonding Evaluation System (ABES), originally designed for wood strands, was extended to test the effect of lay-up on shear strength and percent wood failure for this 3.2 -mm (1/8 -inch) thick veneer. The glue spread was 174 g/m^2 (35 lb/1000 ft^2) per single glueline using normal phenol formaldehyde (PF) for plywood manufacturing. The contact area between two strips was 10 x 20 -mm. The total force applied was about 325 N, equivalent to 1.62 MPa on the contact area. The heating temperature was 155°C. The heating time was 180 sec. with which the glueline can be cured. The glueline temperature was monitored with a thermocouple during glue curing. After heating, the cooling time for glued veneer strips was 100 sec.. Subsequently, the glued samples were pulled apart. The load was recorded accordingly to calculate the shear strength. Furthermore, the failure mode of each sample was examined. Additional tests were conducted with heating time 240 sec. to ensure a full cure of the glue. The loose-to-tight layup was used for both blue-stained veneer and control veneer with fifteen replicates.

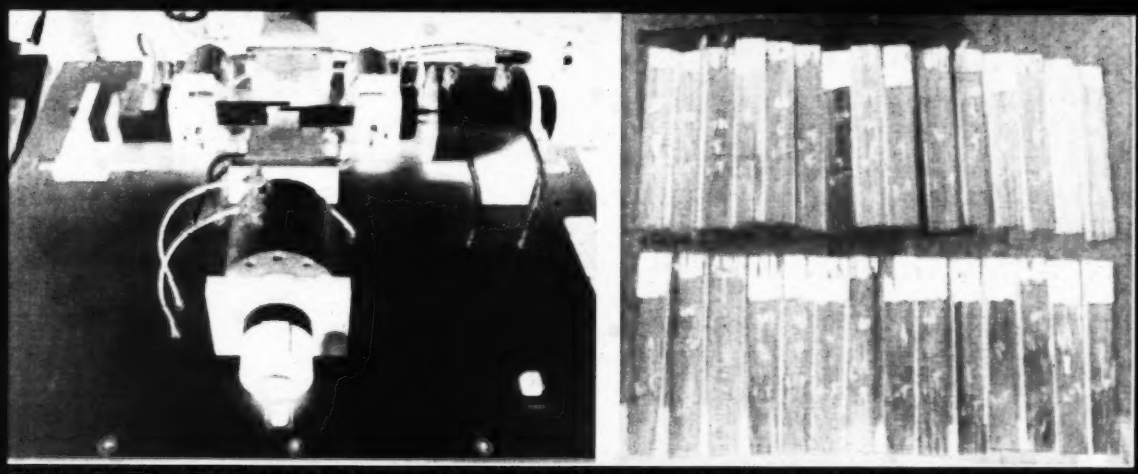


Figure 7: The ABES system for measuring dry bonding strength of the beetle-wood and control veneer

4.1.2.3 Optimization of Panel Lay-up and Assembly Time

To study the effect of veneer temperature, glue spread level and panel assembly time on gluing, shear strength and percent wood failure for both beetle-wood veneer and control veneer, an experimental design was devised to determine the relationships between panel assembly and panel quality. As shown in Table 2, twenty seven (27) 5-ply plywood panels (81.3 x 40.6 -cm) were made with different combinations of glue spread level, veneer temperature and assembly time using the beetle-wood veneer and control veneer, respectively. The assembly time was defined as the time interval between completion of assembly of lay-ups and the application of pressure and heat. To simulate the effect of veneer temperature, veneer sheets were put into the oven at the pre-set temperature for 300 seconds of heating.

Then veneer sheets were covered with a target level of glue spread with a rotary glue spreader. During pressing, the plate pressure was maintained as 1.21 MPa (175 psi), and the temperature rise of the innermost glueline was monitored with two thermocouples. Once the temperature reached the target 110°C, a 30-second decompression cycle started. Control tests were conducted to identify the difference in pressing time, gas pressure (or occurrence of blows) and panel compression ratio (CR). After unloading, panels were hot stacked for 48 hours before cutting, as shown in Figure 8. Four 43.2 x 7.6 -cm (17 x 3 -inch) bending specimens were cut from each panel to measure the panel MOE and MOR (CSA O325.1-88). As well, twenty-four 80 x 25.4 -mm shear test specimens were cut from each panel to measure shear strength and percent wood failure (CSA O151-04). Among 24 specimens, half (12) received vacuum pressure treatments and the other half underwent boiling-dry-boiling treatments. The results help determine the optimum glue spread level and assembly time and whether any changes in plywood gluebond performance are due to surface chemistry or to other processing factors.

Table 2: Test program to measure the effect of glue spread, veneer temperature and panel assembly time on bonding and bending strength of 5-ply beetle-wood plywood and 5-ply control plywood

Experiment no.	X_1 (glue spread) g/m^2 ($lb/1000ft^2$)	X_2 (veneer temperature) °C (°F)	X_3 (assembly time) min	Replicates
1	159 (32.0)	21.1 (70)	10	3
2	159 (32.0)	32.2 (90)	15	3
3	159 (32.0)	43.3 (110)	20	3
4	174 (35.0)	21.1 (70)	15	3
5	174 (35.0)	32.2 (90)	20	3
6	174 (35.0)	43.3 (110)	10	3
7	189 (38.0)	21.1 (70)	20	3
8	189 (38.0)	32.2 (90)	10	3
9	189 (38.0)	43.3 (110)	15	3

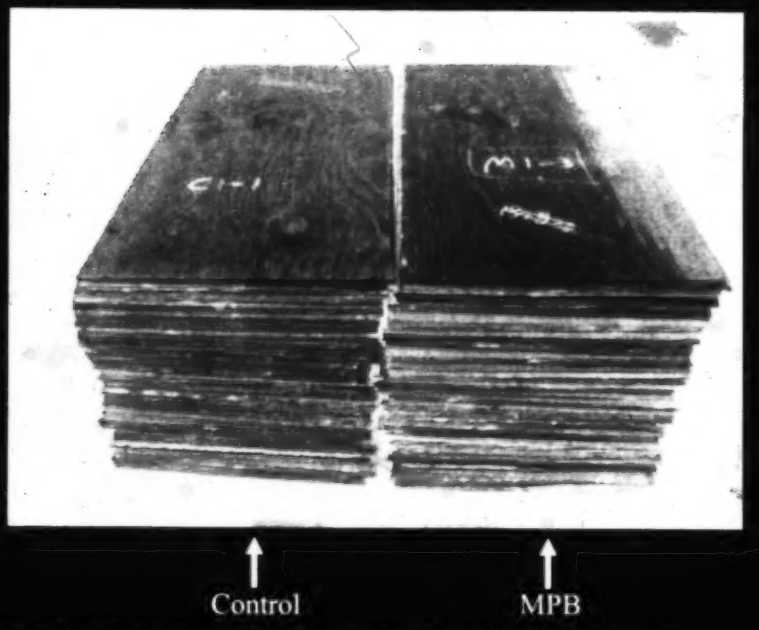


Figure 8: The 5-ply control plywood and beetle-wood plywood

4.1.3 Effect of beetle-wood veneer on plywood/LVL hot-pressing and performance

To optimize the hot-pressing parameters for beetle-wood plywood and LVL, Forintek's 89 x 89 -cm (35 x 35 -inch) computer-controlled press was used to manufacture 5-ply (81.3 x 40.6 -cm) beetle-wood plywood and 13-ply (81.3 x 40.6 -cm) beetle-wood LVL panels.

As shown in Table 3, different combinations of platen pressure, glue spread level and assembly time were investigated for 5-ply beetle-wood plywood panels. During pressing, the temperature rise of the innermost glueline was monitored with two thermocouples. Once the temperature reached target 110°C, a 30-second decompression cycle started. After pressing, the 5-ply plywood panels were hot stacked for 48 hours before cutting. Then four 43.2 x 7.6 -cm (17 x 3 -inch) panel bending specimens and twenty-four 80 x 25.4 -mm shear specimens from each panel were cut. Among 24 shear specimens, half received vacuum pressure treatments and the other half received boiling-dry-boiling treatments. Panel MOE, MOR, percent wood failure and quality were examined using standard test methods (CSA O151-04; CSA O325.1-88).

Table 3: The manufacturing of 5-ply beetle-wood plywood

Experiment no.	X_1 (glue spread) g/m^2 ($lb/1000ft^2$)		X_2 (assembly time) min.		X_3 (platen pressure) MPa (psi)		Replicates
1	159 (32)	L1*	10	L1	1.21 (175)	L2	3
2	159 (32)	L1	15	L2	1.38 (200)	L1	3
3	174 (35)	L2	10	L1	1.38 (200)	L1	3
4	174 (35)	L2	15	L2	1.21 (175)	L2	3

Note: * indicating level of each variable.

To investigate the feasibility of using the beetle-wood veneer for LVL products, four 13-ply beetle-wood LVL billets and four control LVL billets were made using identical manufacturing parameters. For each lay-up, the moisture content (MC) of each veneer sheet was checked and the length, width, weight and 9-point thickness of each veneer sheet were measured and the density calculated. The glue spread was

174 g/m^2 (35 lb/1000 ft^2) per single glueline. During pressing, the platen temperature was kept constant at 155°C. The platen pressure was maintained at 1.21 MPa (175 psi). The temperature rise of the innermost glueline was monitored with two thermocouples, and gas pressure was also monitored during pressing. Once the temperature of the innermost glueline reached 105°C, a 60-second stepwise decompression cycle started. During unloading, the occurrence of blows was carefully monitored. After unloading, panels were hot stacked for 48 hours before cutting. The thickness, weight and MC of each panel were measured, and the compression ratio (CR) and specific gravity of each panel were calculated.

Four 81.3 x 3.8 x 3.8 -cm (32 x 1.5 x 1.5 -inch) edgewise and four 81.3 x 3.8 x 3.8 -cm flatwise bending specimens were cut from each panel for bending stiffness and strength measurement following the standard requirements (ASTM D 198; JAS SIS-24 1993; APA 2000). Six 5.6 x 5.1 x 3.8 -cm (2.2 x 2.0 x 1.5 -inch) longitudinal block shear specimens and six 6.4 x 3.8 x 3.8-cm (2.5 x 1.5 x 1.5 -inch) block shear specimens (ASTM D 143; ASTM D 5456) through-the-thickness were also cut from each panel. After longitudinal shear tests, the failure mode and percent wood failure were estimated. The results help determine the feasibility of the beetle-wood veneer for LVL and quantify the effect of the beetle-wood veneer on manufacturing productivity, material recovery, panel quality and performance,.

4.2 Mill Trial

Approximately 2000 m^3 MPB logs were segregated from the typical white wood mix in the mill before the trial. The mill trial was focused on veneer stress grading, panel gluing, layup and hot-pressing. Based on mill daily quality control records, the process parameters and relevant information on the control white wood veneer from stress grading, lay-up, hot-pressing and gluebond performance were captured. The difference in gluing and pressing behaviour found in the pilot plant tests between 5-ply MPB plywood and 5-ply control plywood was examined in the mill for making 1.2 x 2.4 -m (4 x 8 -feet) panels. Panel gluebond performance such as shear strength and percent wood failure was measured for validation.

4.2.1 Veneer Drying, Stress Grading and Visual Grading

The newly installed No. 5 jet dryer in this mill was used to dry the beetle-wood veneer and control veneer. The target drying temperature and humidity were set at 196°C (385°F) (actual from 177-197°C or 351 – 386°F) and 75% (actual from 15% to 60%) for three zones. The drying outputs were monitored for the beetle-wood veneer and control veneer, respectively. For three sorts of green veneer, namely heavy sap, light sap and heart, the drying times were about 8 min., 7 min. and 5 min. for the beetle-wood veneer, and 10.5 min., 9.0 min. and 6.5 min. for the control veneer. In general, veneer drying yielded 75%-80% of normal dry veneer (level 0) with a peak MC from 0%-6% for both beetle-wood veneer and control veneer by setting the total volume of redry and stacking at a target of 25%. After drying, veneer sheets were first put through the Metriguard model 2600 (with model 2800 upgrade) DFX digital ultrasonic veneer tester. This machine was able to run at 3.05 m/s (423 ft/min) with temperature and MC compensation. The MC was measured using radio frequency technology and veneer specific gravity (or density) was measured using microwave technology. For each veneer sheet, the veneer MOE was calculated and displayed on the control screen. Up to seven grades of veneer plus one reject grade could be sorted. For the beetle-wood veneer, about 4000 sheets from the three sorts were put through the tester. Similarly, for the control veneer, about 3500 sheets from the three sorts were put through the tester. All the data were downloaded from the control panel of the tester. The results will help confirm whether the beetle-wood veneer is denser and stronger than the control veneer and the suitability of the beetle-wood veneer and control veneer for LVL products. After stress grading, all veneer sheets were passed through the newly installed Mecano VDA/DMA/2004 Grader for visual grading. Visual grades included centers, U-lay core, U-lay face, select, X-sheathing, sheathing, JAS, splits, core and redry. Figure 9 shows the drying, stress grading, visual grading and stacking of the beetle-wood veneer.

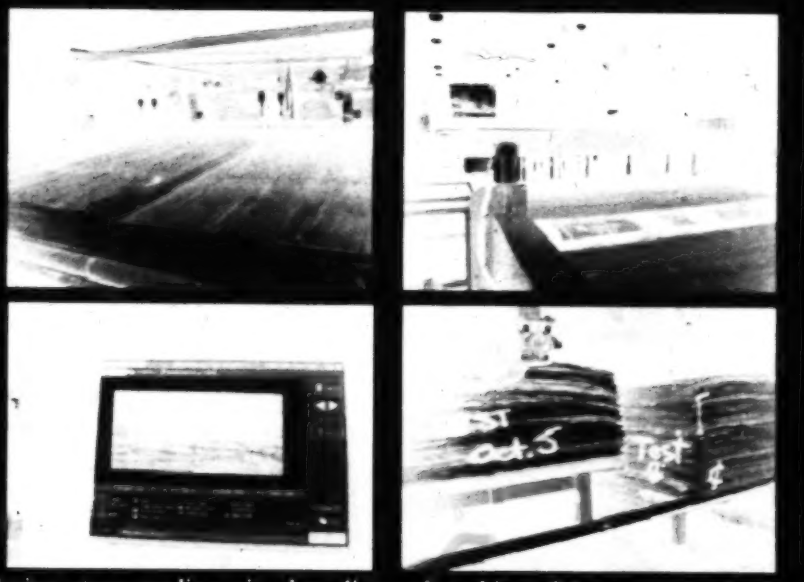


Figure 9: The drying, stress grading, visual grading and stacking of the mountain pine beetle veneer

4.2.2 Panel Gluing and Layup

Two hot presses were used to press 5-ply beetle-wood and control plywood with 36 (press 1) and 30 (press 2) openings. For 5-ply control plywood, the mill current pressing schedules were used with a pressing time of 255 sec. The panel hot-pressing parameters such as platen pressure and pressing temperature were also recorded. One load of control plywood panels was manufactured at each of the press 1 and press 2 for each of the four different glue spread levels: 144, 149, 154, 159 g/m^2 (or 29, 30, 31 and 32 lb/1000 ft^2) per single glueline. Then two plywood panels at each glue-spread level were randomly sampled from 30 panels made at the press 2 for gluebond performance tests.

For 5-ply beetle-wood plywood, the panels were also made using both press 1 and press 2. The panels were made in terms of the three glue spread levels and two pressing time levels, as shown in Table 4. After unloading the panels, three panels from the press 1, and six panels from the press 2 were randomly sampled for gluebond performance tests.

For both control plywood and beetle-wood plywood, total assembly time and veneer temperature were also recorded. The total assembly time included layup, open assembly, closed assembly and standing out time. A camera image system was set up at the glue station to monitor the glue coverage map at different glue spread levels ranging from 144 to 159 g/m^2 (or 29 to 32 lb/1000 ft^2) per single glueline.

Table 4: The experimental design for manufacturing 5-ply MPB plywood

5-ply MPB plywood	Glue spread (X_1) g/m^2 (lb per 1000 ft^2)		Pressing time (X_2) seconds	Press loads*	Sample panels**
1	144	29.0	285	4 (132 panels)	9
2	144	29.0	255	4 (132 panels)	9
3	152	30.5	285	4 (132 panels)	9
4	152	30.5	255	4 (132 panels)	9
5	159	32.0	285	4 (132 panels)	9
6	159	32.0	255	4 (132 panels)	9

Note: *two loads from the press 1 and two loads from the press 2;

**three panels were sampled from 72 panels made at the press 1 randomly, the remaining 6 panels were sampled from 60 panels made at the press 2 randomly.

During pressing, the innermost glueline temperature was monitored with a thermocouple linked with a digital pyrometer EETh501. Although efforts were made to measure the innermost glueline temperature at the centre of the panel, the actual position of the thermocouple was at the corner with about 20 cm - 25 cm inward from the edge. The pressing time for the innermost glueline to reach 100°C was compared between beetle-wood plywood and control plywood. Figure 10 shows the panel gluing, lay-up, pre-pressing and hot pressing of 5-ply beetle-wood plywood with the 30-opening press 2.

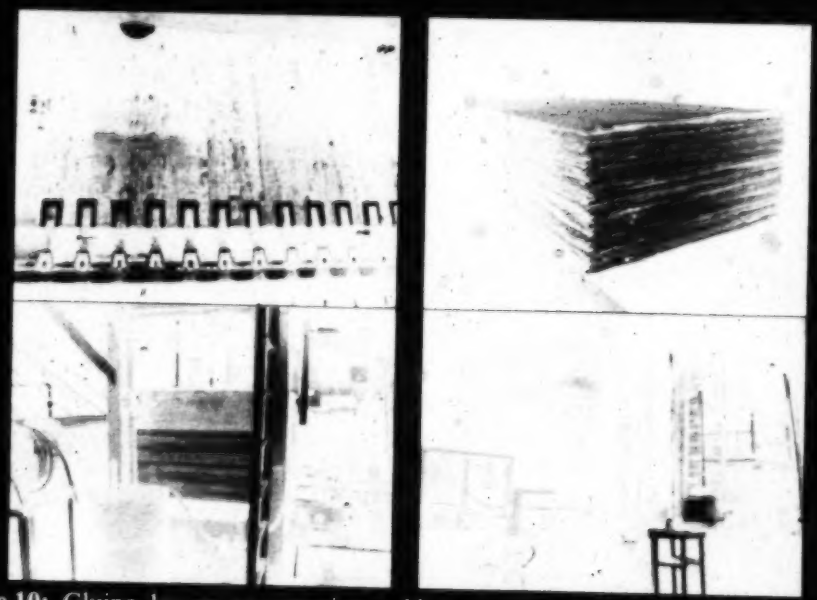


Figure 10: Gluing, lay-up, pre-pressing and hot pressing of 5-ply MPB plywood

4.2.3 Panel Guebond Performance Testing

For each panel sampled, one 30.5 x 122.0 -cm (1 x 4 -ft) sample strip was cut and shipped to Dynea Canada Ltd., a plywood glue supplier, for gluebond performance tests and the remaining 213.4 x 122.0 -cm (7 x 4 -ft) was shipped to Forintek to conduct parallel tests on gluebond performance. For each panel, twelve 80.0 x 25.4 -mm shear test specimens each were cut for vacuum pressure tests at Dynea and Forintek, respectively (Figure 11). The gluebond performance was measured in terms of percent wood

failure and shear strength for 5-ply beetle-wood plywood and control plywood, respectively (CSA O151-04). In addition, based on the mill monthly auditing of plywood quality, the percent wood failure readings of 5-ply control plywood in 2005 were also collected from the mill. The results were recorded which help confirm the wet gluebond performance of beetle-wood plywood is better than that of control plywood, and beetle-wood plywood requires slightly longer pressing time. At Forintek, six 43.2 x 7.6 -cm (17 x 3 -inch) bending specimens were also cut from each panel for measuring bending MOE and MOR (CSA O325.1-88). The results will help determine whether beetle-wood plywood is stronger than control plywood and whether glue spread and pressing time should be adjusted for beetle-wood plywood.

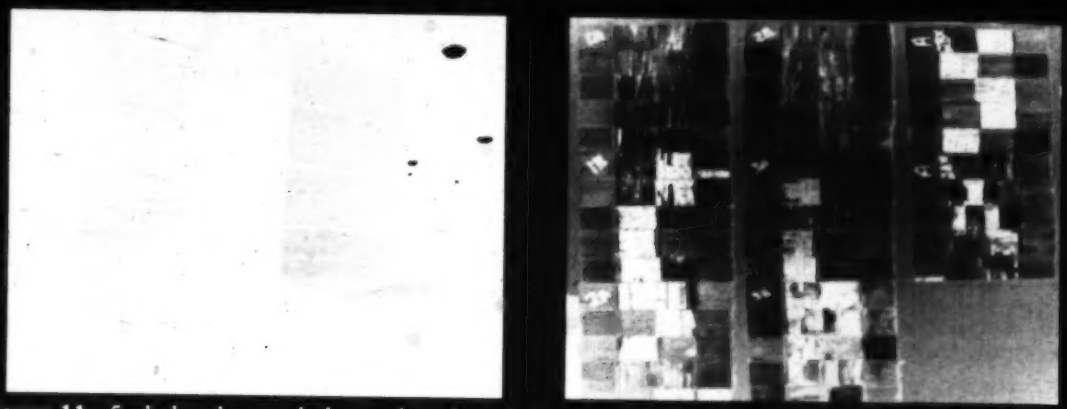


Figure 11: 5-ply beetle-wood plywood made and shear samples cut for gluebond performance tests

5 Results and Discussion

5.1 Pilot plant testing

5.1.1 Quality, visual and stress grading of beetle-wood veneer

5.1.1.1 Veneer stress grading

As shown in Tables 5 and 6, the t-tests were used to investigate the difference in mean veneer density, mean stress wave time (equivalent to UPT) and mean dynamic MOE between the beetle-wood veneer and control veneer. It was found that the average and within-sheet variation of the stress wave time of the beetle-wood veneer were significantly larger than those of the control veneer at the $p = 0.05$ level probably due to more cracks (or splits) and micro-checks on the beetle-wood veneer sheets, as shown in Figure 3. Among 36 beetle-wood veneer sheets, 19 had one or two long cracks or splits. As well, the density of the beetle-wood veneer was significantly higher than the control veneer at the $p = 0.05$ level. This result seemed to contradict data from one study indicating the density of the beetle-killed wood was lower than that of control lodgepole pine wood (Woo et al. 2005). This is possibly due to the fact that the control veneer was a mixture of lodgepole pine, white spruce and subalpine fir among which white spruce and subalpine fir had a lower density than lodgepole pine. Furthermore, the MOE of the beetle-wood veneer was significantly different from that of the control veneer at the $p = 0.05$ level. On average, the beetle-wood veneer was about 7.9% higher in MOE than the control veneer.

Veneer stress grading can add value recovery to the beetle-wood veneer by making structural LVL and specialty plywood products. Since the beetle-wood veneer had the larger UPT than the control veneer, if mills perform stress grading based on the UPT, the grade outturns could be lower from the beetle-wood veneer than those from the control veneer. However, if mills perform MOE-based stress grading, the grade outturns will be higher from the beetle-wood veneer. To maximize the grade outturns and value recovery, it is recommend that mills use MOE stress rating for this resource.

Table 5: The t-test results for mean stress wave time of veneer sheets

Comparison	Veneer stress wave time (μs)*			
	Average per sheet		Within-sheet variation	
	MPB	Control	MPB	Control
Mean	152.5	147.9	8.2	5.5
Variance	99.1	120.1	14.9	9.5
Observations	36	36	36	36
Hypothesized mean difference	0	$\lvert t\rvert > t_{critical}$	0	$\lvert t\rvert > t_{critical}$
df	35		35	
t Stat	2.08		3.92	
P(T<=t) one-tail	0.022		0.00020	
t Critical one-tail	1.69		1.69	
P(T<=t) two-tail	0.044		0.00040	
t Critical two-tail	2.03		2.03	

Note: * for a span of 76.2 cm (30 inches)

Table 6: The t-test results for veneer density and MOE

Comparison	Veneer density (g/cm^3)		Veneer MOE (MPa / 10^6 psi)	
	Average per sheet		Average per sheet	
	MPB	Control*	MPB	Control
Mean	0.447	0.390	11300 / 1.64	10438 / 1.52
Variance	0.0018	0.0020	462 / 0.067	386 / 0.056
Observations	36	36	36	36
Hypothesized mean difference	0	$t > t_{critical}$	0	$t > t_{critical}$
df	35		35	
t Stat	5.26		11.03	
P(T<=t) one-tail	3.65E-06		3.05E-13	
t Critical one-tail	1.69		1.69	
P(T<=t) two-tail	7.30E-06		6.10E-13	
t Critical two-tail	2.03		2.03	

Note: * a typical mix of lodgepole pine, white spruce and subalpine fir.

5.1.1.2 Dry Veneer Quality

Based on the results from veneer stress grading, about 53% of the dried beetle-wood veneer sheets had long cracks or splits, which is probably due to 1) dryout of logs after beetle attack; and/or 2) over-drying of veneer. To investigate the effect of beetle-induced blue stain on veneer quality attributes and properties, blue-stained veneer sheets were segregated from non-stained veneer sheets based on visual inspection. Among 36 beetle-wood veneer sheets used for stress grading, there were 13 full blue-stained, 12 partial blue-stained and 11 non-stained heartwood veneer sheets. It was found that the cracks or splits were present on both blue-stained veneer and non-stained veneer. The previous study showed that beetle-wood logs generated about 2% more volume of random width veneer, which was 38.3% narrower than that from control logs (Wang and Dai 2004). Overdrying-induced cracks or splits could significantly affect veneer handling, composing, gluing, panel gluebond quality and material recovery. As a result, developing optimum dry schedules for the beetle-wood veneer is essential to the mill to maximize the value recovery of beetle-wood logs for plywood/LVL manufacturing.

Table 7 shows a comparison of veneer quality attributes and properties of full blue-stained, partial blue-stained and non-stained veneer. Since blue-stained veneer was mainly produced from the sapwood of beetle-wood logs, it had higher density, higher MOE and shorter stress wave time compared with non-stained veneer.

Table 7: Comparison of mountain pine beetle blue-stained veneer and mountain pine beetle non-stained veneer

MPB veneer	Density (g/cm^3)		Thickness (mm / inch)		Stress wave time** (s)		MOE (MPa / MMpsi)	
	Average	Std. Dev.*	Average	Std. Dev.*	Average	Std. Dev.*	Average	Std. Dev.*
Full blue-stained	0.452	0.039	3.249 / 0.1280	0.101 / 0.0040	151	6.2	11575 / 1.68	1536 / 0.223
Partial blue-stained	0.454	0.050	3.244 / 0.1277	0.107 / 0.0042	150	7.1	11713 / 1.70	1935 / 0.281
Non-stained	0.435	0.048	3.239 / 0.1275	0.134 / 0.0053	156	15.4	10680 / 1.55	2184 / 0.317

Note: * between-sheet variation

** for a span of 76.2 cm (30 inches)

As shown in Table 8, there were 324 data points each for thickness of 36 beetle-wood veneer and 36 control veneer sheets, respectively, representing the population of dry veneer thickness. Under the same log conditioning and peeling parameters, while not statistically significant at the $p = 0.05$ level, the dried beetle-wood veneer was slightly thicker and had larger thickness variation than the dried control veneer, which is probably due to the rougher surface and less radial shrinkage of the beetle-wood veneer. Note that the MC of some beetle-wood veneer was below the fibre saturation point. As shown in Table 9, on the sheet basis, the t-test results also show that there was no significant difference in average veneer thickness and within-sheet thickness variation between the beetle-wood veneer and control veneer at the $p = 0.05$ level.

Table 8: The t-test results for thickness of dry veneer population

Comparison of dry veneer thickness (mm)	MPB veneer	Control veneer
Mean	3.246	3.235
Variance	0.045	0.037
Observations	324	324
Hypothesized Mean Difference	0	$\lvert t \rvert < t_{critical}$
df	639	
t Stat	0.717	
P(T<=t) one-tail	0.237	
t Critical one-tail	1.647	
P(T<=t) two-tail	0.474	
t Critical two-tail	1.964	

Table 9: The t-test results for average thickness of dry veneer sheets

Comparison	Dry veneer thickness (mm / inch)			
	Average per sheet		Within-sheet variation	
	MPB	Control	MPB	Control
Mean	3.246 / 0.128	3.235 / 0.127	0.180 / 0.0071	0.158 / 0.0062
Variance	0.0122	0.0118	0.0051	0.0037
Observations	36	36	36	36
Hypothesized mean difference	0	$\lvert t \rvert < t_{critical}$	0	$\lvert t \rvert < t_{critical}$
df	35		35	
t Stat	0.431		1.411	
P(T<=t) one-tail	0.335		0.084	
t Critical one-tail	1.690		1.690	
P(T<=t) two-tail	0.669		0.167	
t Critical two-tail	2.030		2.030	

From the compression tests, the load-displacement curve of each small veneer piece was recorded. The minimum compression required to achieve adequate contact was identified under a 100-kg threshold load for each veneer piece. In general, the larger the minimum compression required, the rougher the veneer surface (Wang et al. 2006a; Wang et al. 2006b). As shown in Table 10, the t-test was conducted to compare the veneer roughness and compressibility between the beetle-wood veneer and control veneer. There was no significant difference in the minimum compression required between the beetle-wood veneer and control veneer. While not statistically significant at the 0.05 level, beetle-wood veneer appeared to be rougher (the roughness index is 4.5% larger) than the control veneer.

Table 10: The t-test results for minimum compression required (indication of veneer roughness)

Comparison	Minimum compression required (mm)	
	MPB veneer	Control veneer
Mean	0.301	0.288
Variance	0.0027	0.0020
Observations	38*	40
Hypothesized mean difference	0	$\lvert t \rvert < t_{critical}$
df	73	
t Stat	1.19	
P(T<=t) one-tail	0.119	
t Critical one-tail	1.67	
P(T<=t) two-tail	0.24	
t Critical two-tail	1.99	

Note: *two were broken.

In summary, the beetle-wood dry veneer appeared to be rougher and slightly thicker than the control dry veneer. About 53% of dried beetle-wood veneer sheets had long splits or cracks, probably due to the

dryout of logs and veneer over-drying. Similar to the control veneer, over-drying of the beetle-wood veneer would worsen glueline dryout and cause panel delamination. Developing optimum drying schedules for the beetle-wood veneer is essential to maximize the value recovery of beetle-wood logs for plywood/LVL manufacturing.

5.1.1.3 Veneer Visual Grading

As shown in Figure 12, there were different levels of blue stain on the beetle blue-stained veneer. Similarly, as shown in Figure 13, the whiteness of the control veneer also varied from veneer to veneer. Due to some current market issues plus the fact that current visual grading system used by some plywood/LVL mills cannot detect veneer defects within the blue-stained area (Wang and Dai 2004), study of the visual characteristics of blue stain is required. To effectively differentiate the blue-stained veneer from the non-stained veneer, an analysis of the colour difference and colour distribution was conducted.

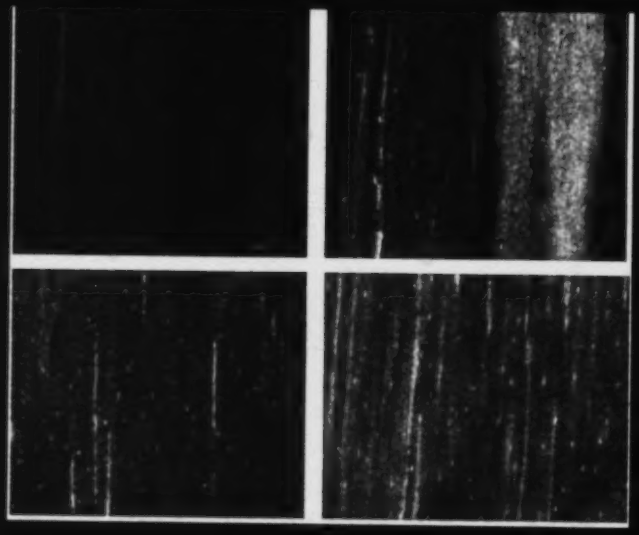


Figure 12: Images of beetle-wood veneer with different levels of blue stain

Figure 13: Images of control veneer

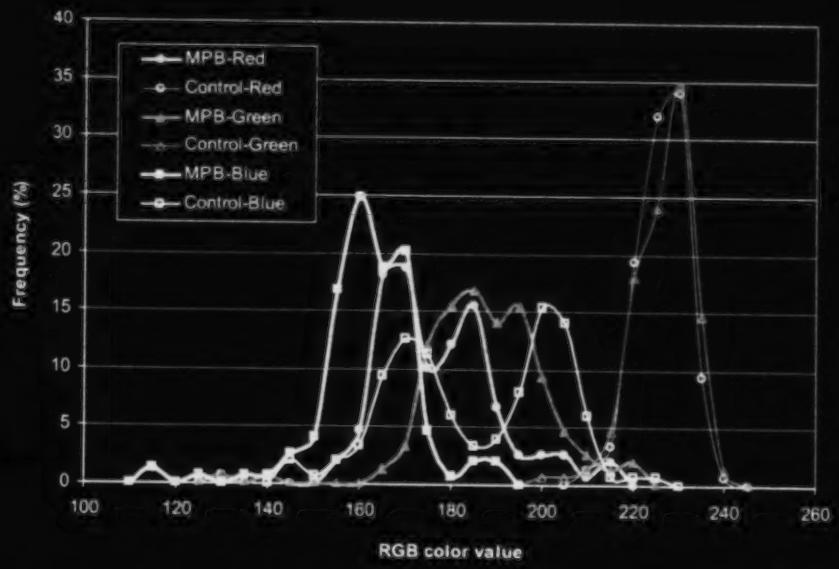


Figure 14: The frequency distribution of RGB values for the beetle-wood veneer and control veneer

As shown in Figure 14, the frequency distribution of Red, Green and Blue (RGB) values was plotted for both beetle-wood veneer and control veneer. A small overlapping in both Red and Green existed between the beetle-wood veneer and control veneer, but a significant overlapping existed in Blue colour between the beetle-wood veneer and control veneer. The results showed that the blue-stained veneer could be basically segregated from the normal control veneer based on either Red or Blue color values or a combination of both.

To further identify the unique color characteristics of the blue-stained veneer, the frequency distribution of the three alternative color indexes: Hue, Saturation and Luminance (HSL) was plotted for both beetle-wood veneer and control veneer, as shown in Figure 15. The results showed that the degree of overlapping between the beetle-wood veneer and control veneer decreased from Luminance to Hue and then to Saturation. Compared to the Red and Green color values, the Saturation index (%) resulted in the least overlapping between the blue-stained veneer and control veneer. This demonstrated that Saturation index (%) could be more effectively used to segregate the blue-stained veneer from the non-stained veneer and control veneer.

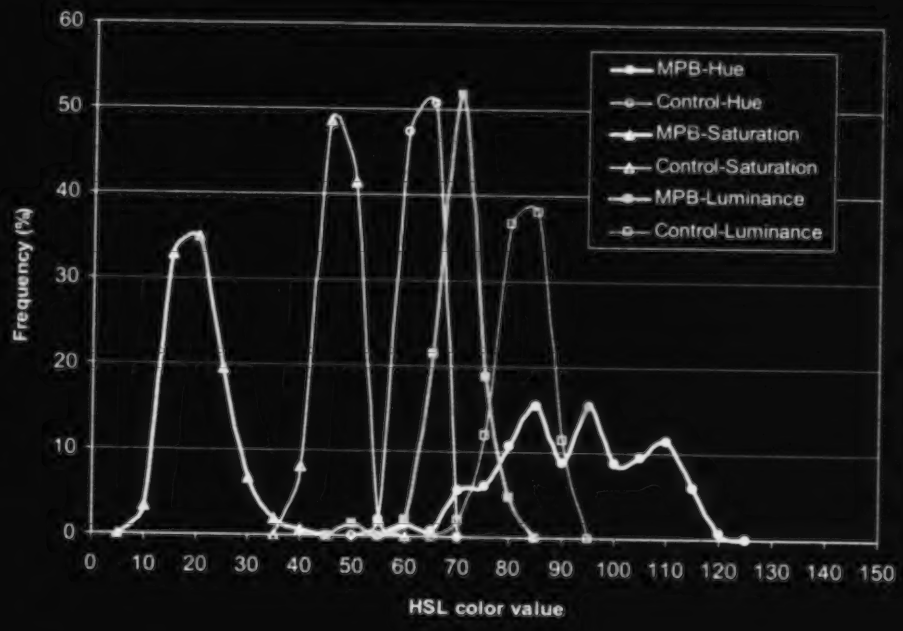


Figure 15: The frequency distribution of HSL indexes for the beetle-wood veneer and control veneer

To further look into the feasibility of using the Saturation index for segregating blue stain from other veneer characteristics, as shown in Figure 16, the colour Saturation index of the control veneer, blue-stained veneer, dark knots, cracks and knot perimeters were compared. The results demonstrated that the blue-stained veneer had the lowest colour Saturation index (%) with values from 5 to 65 with which blue stain could be isolated from veneer defects, non-stained veneer and normal control veneer.

Additionally, the combination of Saturation and Hue or Red and Green can also be tested for the purpose of distinguishing blue stain from other defects. As long as the colour threshold is established, the existing visual grading camera systems used by some plywood/LVL mills can be upgraded to sort for blue-stained veneer or mask blue stain during veneer visual grading.

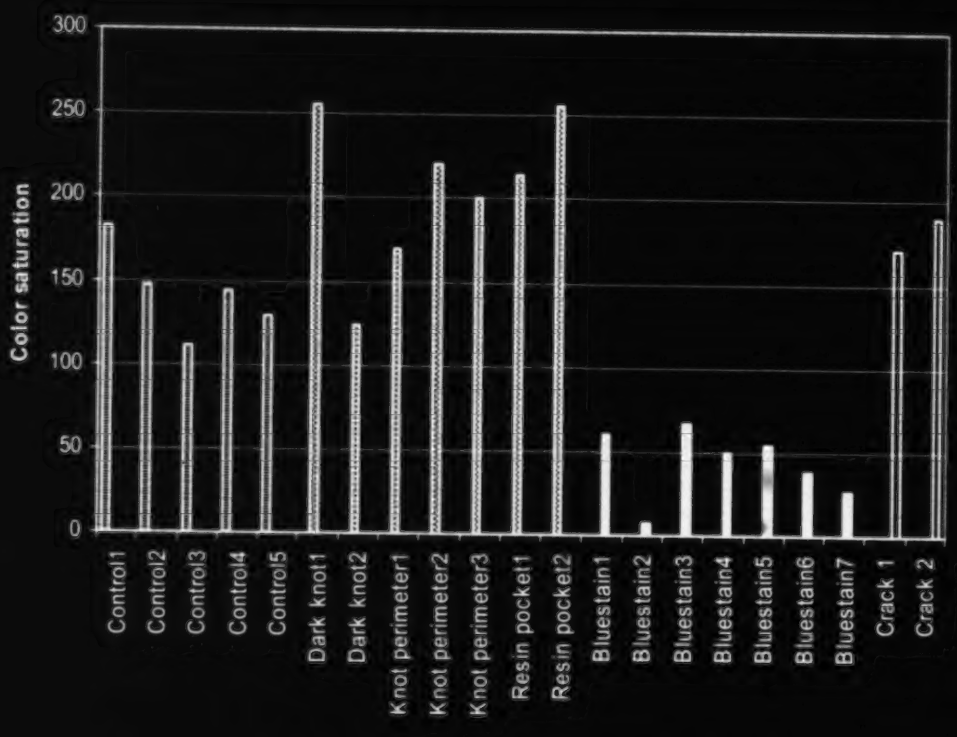


Figure 16: Color saturation index (%) for different veneer characteristics

In summary, current machine vision technology used by some plywood/LVL mills cannot differentiate veneer defects within the blue-stained area, hence it is unable to sort the beetle-wood veneer in its current configuration. Compared to common Red, Green and Blue (RGB) color values, saturation index (%) in the Hue, Saturation and Luminance (HSL) color space effectively differentiated blue stain from veneer defects with the least overlapping between the blue-stained veneer and control veneer. As a result, by adjusting the color detection algorithm in the software, the current machine vision systems can be upgraded to visually segregate the blue-stained veneer or to mask the effect of blue stain during sorting. Interested mills should check with their equipment vendor.

5.1.2 The Effect of Mountain Pine Beetle Veneer on Gluing, Panel Lay-up, Shear Strength and Percent Wood Failure

5.1.2.1 Veneer Transverse Air Permeability

As shown in Table 11, the t-tests indicated that for the beetle-wood veneer, the transverse air permeability between the blue-stained veneer and non-stained veneer was significantly different. On average, the air permeability of the blue-stained veneer (beetle-killed sapwood) was about 2.8 times that of non-stained veneer (beetle-killed heartwood). This is consistent with those from other studies showing that the permeability of sapwood is generally higher than that of heartwood (Wang et al. 2006).

Table 11: Comparison of permeability of the beetle-wood blue-stained veneer and beetle-wood non-stained veneer

Comparison	Air permeability of MPB veneer (m^2)	
	Sapwood (blue-stained)	Heartwood (non-stained)
Mean	3.75E-13	1.33E-13
Variance	1.51E-26	1.54E-26
Observations	15	16
Hypothesized mean difference	0	$\lvert t \rvert > t_{critical}$
Df	29	
t Stat	5.5	
P(T<=t) one-tail	0.0000036	
t Critical one-tail	1.7	
P(T<=t) two-tail	0.0000072	
t Critical two-tail	2.0	

In Table 12, the t-tests showed that on average, the beetle blue-stained veneer was about 23% higher in air permeability compared to the control veneer, however, they were not statistically different at the p = 0.05 level. As well, the air permeability between the beetle-wood veneer and control veneer was not statistically different at the p = 0.05 level. The results indicate that during hot pressing of beetle-wood plywood/LVL panels, the rate of heat convection could be still limited as commonly experienced in the hot pressing of control plywood/LVL made from typical white wood mixed veneer. Instead, veneer density could be the key factor affecting heat transfer efficiency.

Table 12: Comparison of permeability of the mountain pine beetle blue-stained veneer, beetle-wood veneer and control veneer

Comparison	Veneer air permeability (m^2)			
	MPB blue-stained veneer	Control veneer*	MPB veneer	Control veneer*
Mean	3.8E-13	3.1E-13	2.5E-13	3.1E-13
Variance	1.5E-26	5.8E-26	3.0E-26	5.8E-26
Observations	15	13	31	13
Hypothesized Mean Difference	0	$\lvert t \rvert < t_{critical}$	0	$\lvert t \rvert < t_{critical}$
Df	17		17	
t Stat	0.935		-0.762	
P(T<=t) one-tail	0.182		0.228	
t Critical one-tail	1.740		1.740	
P(T<=t) two-tail	0.363		0.456	
t Critical two-tail	2.110		2.110	

Note: *a mix of lodgepole pine, white spruce and subalpine fir veneer

As shown in Table 13, the air permeability of the two-ply beetle-killed heartwood panels was significantly higher than that of the two-ply control lodgepole pine heartwood panels at the p = 0.05 level. While not statistically different at the p = 0.05 level, the air permeability of the two-ply beetle-killed sapwood panels was about 1.5 times that of the two-ply control lodgepole pine sapwood panels. The implication is that the

permeability of the beetle-wood veneer increased compared to that of control lodgepole pine veneer. The drying rate, the rate of heat convection and preservative uptake of the beetle-wood veneer would be relatively higher compared to those of the control lodgepole pine veneer segregated from the typical white wood mix.

Table 13: Comparison of air permeability of sapwood and heartwood panels made from the beetle-wood veneer and control lodgepole pine veneer

Comparison	Permeability of two-ply sapwood panels (m^2)		Permeability of two-ply heartwood panels (m^2)	
	MPB sapwood (blue-stained)	Control sapwood*	MPB heartwood (non-stained)	Control heartwood*
Mean	2.62E-13	1.74E-13	1.81E-13	1.04E-13
Variance	4.36E-26	2.17E-26	1.05E-26	3.20E-27
Observations	23	22*	22	11*
Hypothesized mean difference	0	$\|t\| < t_{critical}$	0	$\|t\| > t_{critical}$
Df	40		31	
t Stat	1.65		2.79	
P(T<=t) one-tail	0.054		0.0044	
t Critical one-tail	1.68		1.7	
P(T<=t) two-tail	0.108		0.0089	
t Critical two-tail	2.02		2.04	

Note: *only lodgepole pine veneer panels were considered.

In summary, the MPB blue-stained sapwood veneer was about 1.8 times more permeable than non-stained beetle-killed heartwood veneer. However, the permeability of the beetle-wood veneer was not statistically different from that of the control veneer due to the species mix in the control veneer. While not statistically different at the $p = 0.05$ level, the permeability of the MPB blue-stained veneer was about 23% higher than that of the control veneer. Permeability tests of the two-ply panels demonstrated that the permeability of beetle-wood panels was about 1.5-1.7 times that of control lodgepole pine panels. Although the transverse air permeability of the beetle-wood veneer increased compared to that of the control lodgepole pine veneer, the rate of heat convection during panel hot pressing could be similar between the beetle-wood veneer and control veneer without/with lodgepole pine segregation considering their difference in the magnitude of air permeability.

5.1.2.2 pH and Lap-shear Tests

As seen from Figure 6, it seemed that there is no significant difference in pH value between blue-stained veneer and non-stained veneer with a value from 4.0 - 5.0. Table 14 shows the results from shear strength testing with the ABES system. It was found that the glueline temperature ranged from 115 to 125 °C after heating 180 sec. After 100 -second cooling, the glueline temperature was about 100°C when the tensile loading in the ABES machine commenced. In the additional tests with 240 -second heating, maximum airflow was introduced to reduce the temperature after pressing as much as possible. The corresponding glueline temperature at the time of tensile pulling was about 85 - 95 °C.

Table 14: The shear strength of different veneer lay-ups

Lay-up type	Veneer type (X_1)	Construction (X_2)	Shear strength (MPa / psi)	
			Average	Std. Dev.
A	Blue-stained - blue-stained	Loose side to loose side	1.60 / 232	0.43 / 62.9
B	Blue-stained - blue-stained	Loose side to tight side	1.92 / 278	0.56 / 80.5
C	Blue-stained - control	Loose side to loose side	1.58 / 229	0.41 / 59.6
D	Blue-stained - control	Loose side to tight side	1.88 / 273	0.66 / 95.2
E	Control - control	Loose side to loose side	1.68 / 244	0.49 / 70.7
F	Control - control	Loose side to tight side	1.65 / 239	0.44 / 64.1
BB*	Blue-stained - blue-stained	Loose side to tight side	3.25 / 471	0.72 / 103.8
FF*	Control - control	Loose side to tight side	2.42 / 351	0.63 / 91.8

Note: *additional lay-up tests with long heating time (240 sec.) and maximum cooling

With 180 -second heating time, among six lay-ups from A to F, lay-up types B and D had higher shear strength. Compared to loose-to-loose construction, gluing veneer loose-side to tight-side resulted in higher shear strength for both blue-stained-to-blue-stained and blue-stained-to-control veneer constructions. The difference in shear strength was found to be statistically different at the $p = 0.1$ level for above two veneer constructions. Additional lay-up tests BB* and FF* demonstrated that: 1) by gluing loose side to tight side, using the blue-stained veneer resulted in significantly higher shear strength compared to using the control veneer at the $p = 0.05$ level; and 2) the longer heating time and lower temperature at the tensile pulling contributed to the higher shear strength.

In summary, the gluing and lay-up tests demonstrated that veneer loose-to-tight construction improved the panel shear strength for both beetle-wood veneer and control veneer or their combination. By gluing veneer loose side to tight side, using the blue-stained veneer resulted in significantly higher dry shear strength compared to using the control veneer. Therefore, the beetle blue-stained veneer had a positive effect on the dry bonding strength.

5.1.2.3 Optimization of Panel Lay-up and Assembly Time

In order to test plywood shear strength and percent wood failure, the shear specimens were required to receive both vacuum pressure and boiling-dry-boiling cycle treatments. Table 15 shows the comparison of shear strength and percent wood failure from the vacuum pressure tests of 5-ply beetle-wood plywood and control plywood panels. Similarly, Table 16 shows the comparison of shear strength and percent wood failure from the boiling-dry-boiling cycle tests of 5-ply beetle-wood plywood and control plywood panels, respectively. Each data point was the average of 36 plywood shear specimens from the three panels.

Based on the vacuum pressure tests, under different combinations of glue spread, veneer temperature and assembly time, the shear strength of beetle-wood plywood was consistently higher than that of control plywood. As well, the average percent wood failure of beetle-wood plywood was about 10% higher than that of control plywood. Similarly, based on the boiling-dry-boiling cycle tests, under different combinations of glue spread, veneer temperature and assembly time, the average shear strength of

beetle-wood plywood was slightly lower than that of control plywood. However, average percent wood failure of beetle-wood plywood was about 27% higher than that of control plywood.

Note that for both vacuum pressure and boiling-dry-boiling tests, the average percent wood failure of beetle-wood plywood exceeded 80% standard requirements under various gluing and lay-up conditions. In contrast, the average percent wood failure of control plywood panels did not meet the standard requirements.

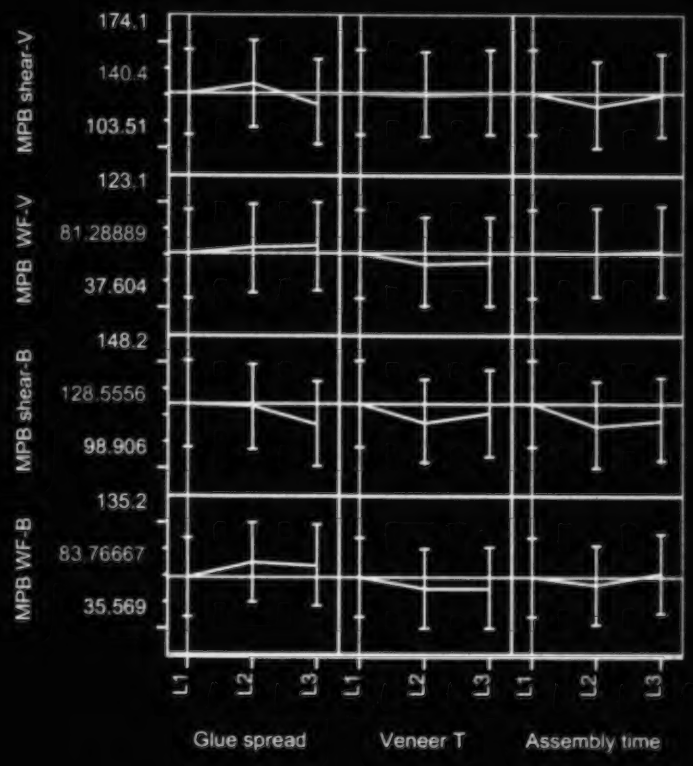
Table 15: Comparison of plywood shear strength and percent wood failure between the beetle-wood veneer and control veneer from vacuum pressure tests

Experiment no.	Glue spread	Veneer temperature	Assembly time	Vacuum pressure			
				MPB veneer		Control veneer	
	X_1	X_2	X_3	Shear strength	Wood failure	Shear strength	Wood failure
	g/m2 (lb/1000ft2)	°C (°F)	(min)	MPa (psi)	(%)	MPa (psi)	(%)
1	159 (32.0)	21.1 (70)	10.0	1.003 (145.3)	86.2	0.909 (131.7)	49.3
2	159 (32.0)	32.2 (90)	15.0	0.882 (127.8)	75.0	0.813 (117.8)	84.7
3	159 (32.0)	43.3 (110)	20.0	0.940 (136.2)	69.7	0.826 (119.7)	76.2
4	174 (35.0)	21.1 (70)	15.0	0.928 (134.5)	81.1	0.883 (127.9)	66.0
5	174 (35.0)	32.2 (90)	20.0	1.021 (148.0)	84.9	0.904 (130.9)	70.4
6	174 (35.0)	43.3 (110)	10.0	0.994 (144.0)	79.3	0.795 (115.3)	78.8
7	189 (38.0)	21.1 (70)	20.0	0.892 (129.3)	90.3	0.802 (116.2)	91.5
8	189 (38.0)	32.2 (90)	10.0	0.891 (129.1)	73.6	0.761 (110.3)	66.2
9	189 (38.0)	43.3 (110)	15.0	0.891 (129.2)	85.5	0.742 (107.5)	77.5
Average				0.938 (135.9)	80.6	0.826 (119.7)	73.4

Table 16: Comparison of plywood shear strength and percent wood failure between the beetle-wood veneer and control veneer from boiling-dry-boiling cycle tests

Experiment no.	Glue spread	Veneer temperature	Assembly time	Boiling dry boiling cycle			
				MPB veneer		Control veneer	
	X_1	X_2	X_3	Shear strength	Wood failure	Shear strength	Wood failure
	g/m2 (lb/1000ft2)	°C (°F)	(min)	MPa (psi)	(%)	MPa (psi)	(%)
1	159 (32.0)	21.1 (70)	10.0	0.911 (132.0)	89.5	0.914 (132.4)	48.9
2	159 (32.0)	32.2 (90)	15.0	0.750 (108.6)	60.3	0.788 (114.3)	83.6
3	159 (32.0)	43.3 (110)	20.0	0.798 (115.6)	76.6	0.838 (121.4)	67.2
4	174 (35.0)	21.1 (70)	15.0	0.800 (116.0)	90.6	0.856 (124.0)	46.3
5	174 (35.0)	32.2 (90)	20.0	0.799 (115.8)	95.9	0.824 (119.4)	47.4
6	174 (35.0)	43.3 (110)	10.0	0.840 (121.7)	81.8	0.793 (114.9)	73.2
7	189 (38.0)	21.1 (70)	20.0	0.763 (110.6)	92.3	0.775 (112.3)	81.0
8	189 (38.0)	32.2 (90)	10.0	0.758 (109.9)	84.0	0.802 (116.3)	73.4
9	189 (38.0)	43.3 (110)	15.0	0.751 (108.9)	83.2	0.751 (108.9)	73.4
Average				0.796 (115.4)	83.8	0.816 (118.2)	66.0

To further investigate the relative importance of the three main manufacturing variables: glue spread, veneer temperature and assembly time on plywood panel shear strength and percent wood failure, a statistical software program, JMP, was used (SAS Institute Inc. 1995). Figures 17 and 18 show the sensitivity analysis of the three variables to shear strength and percent wood failure for 5-ply beetle-wood plywood and control plywood, respectively. Based on the screening effect provided by the JMP statistical software, the relative importance of the three variables to each criterion can be determined by comparing the maximum differences in magnitude of responses from the criterion with respect to the three designated levels of each variable (SAS Institute Inc. 1995). In general, the larger the difference is, the more important the variable will be.



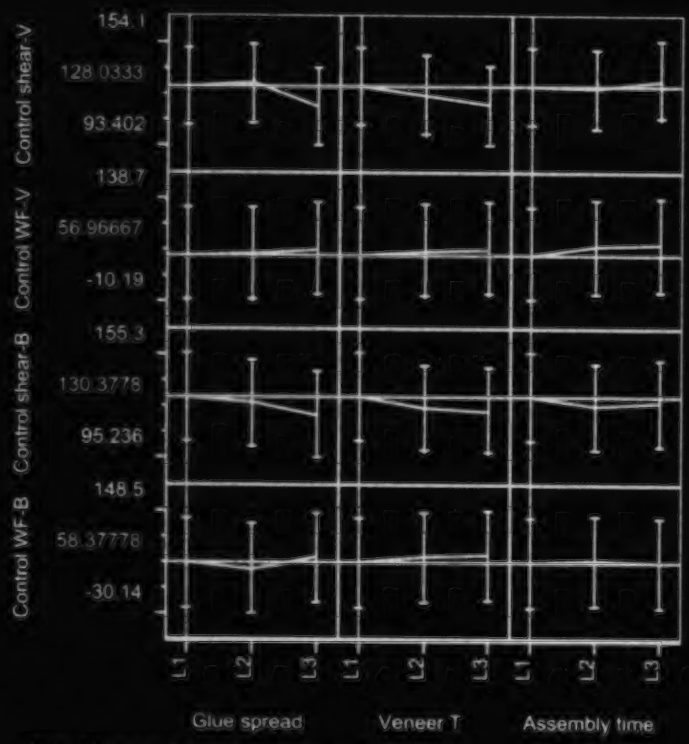
Note: V- stands for vacuum pressure; B-stands for boiling-dry-boiling cycle treatment and T stands for temperature

Figure 17: The sensitivity of the three variables on mountain pine beetle plywood shear strength and percent wood failure

As shown in Figure 17, for beetle-wood plywood, as far as shear strength and percent wood failure are concerned, the most important variable is glue spread, followed by veneer temperature and assembly time. To increase both shear strength and percent wood failure, the optimum glue spread seems to be the middle level (L2) 174 g/m^2 or 35 lb/1000ft^2 per single glueline. When the glue spread level continues to increase, all properties decrease except the percent wood failure from vacuum pressure tests. Veneer temperature has a detrimental effect on both shear strength and percent wood failure since high veneer temperature will lead to glue dryout and panel delamination. In addition, assembly time has some effect on shear strength and percent wood failure. In general, the short assembly time at the lowest level L1 (10 min.) helps increase both shear strength and percent wood failure. The best combination of the three variables under the scope of this experiment is: glue spread 174 g/m^2 per single glueline, veneer temperature 21.1°C (70 °F) and assembly time 10 min. However, based on Figure 17, to reduce the glue consumption, in turn the manufacturing cost, glue spread could be reduced to 159 g/m^2 meeting the minimum requirement of 80% wood failure.

Similarly, as shown in Figure 18, for control plywood, as far as shear strength and percent wood failure are concerned, glue spread and veneer temperature seem to have equal importance, followed by assembly time. To increase both shear strength and percent wood failure from both vacuum pressure and boiling-dry-boiling cycle tests, the optimum glue spread seems to be the lowest level (L1) at 159 g/m^2 or 32 lb/1000ft^2 per single glueline. When the glue spread increases from lowest level (L1) to the middle

level (L2), although both shear strength and percent wood failure increase slightly from vacuum pressure tests, they tend to decrease from the boiling-dry-boiling cycle tests. Veneer temperature seems to affect shear strength more than percent wood failure. Although the percent wood failure slightly increases with the temperature, its magnitude still fails to meet the 80% standard requirement and the shear strength decreases more with the veneer temperature. It seems that the bigger difference in panel gluebond performance between the beetle-wood veneer and control veneer is the percent wood failure instead of shear strength. To increase the percent wood failure of control plywood, assembly time at the middle level (L2, 15 min) seems to be the best. Therefore, the best combination of the three variables under the scope of this experiment for the control veneer is: glue spread L1: 159 g/m^2, veneer temperature from L1 to L2: 21.1°C (70° F) to 32.2°C (90°F) and assembly time L2: 15 min.



Note: V- stands for vacuum pressure; B-stands for boiling dry and boiling cycle treatment and T stands for temperature

Figure 18: The sensitivity of the three variables on control plywood shear strength and percent wood failure

The beetle-wood veneer and control veneer displayed dramatic differences in gluing and wet bonding properties. Compared to using control veneer, using beetle-wood veneer not only resulted in higher dry shear strength, but also higher wet shear strength from vacuum pressure tests and higher percent wood failure from both vacuum pressure and boiling-dry-boiling tests. Increasing glue spread slightly or reducing assembly time and veneer temperature helped increase the shear strength and percent wood failure for beetle-wood plywood. However, with the current glue spread level used for control plywood at 159 g/m^2 per single glueline, the minimum requirement of percent wood failure of beetle-wood plywood can still be achieved. It seems that the changes in beetle-wood plywood bondability are due to a change of surface chemistry. One separate study indicated that following beetle attack, wood morphology and chemistry undergo significant changes due to the defensive mechanism of trees when attacked. The

beetle-killed sapwood had lower hemicellulose/lignin contents and contained significantly lower concentrations of extractives when compared to the control lodgepole pine sapwood. Blue-stained beetle wood contained higher fatty and resin acid proportions (Woo et al. 2005). Although increased resin acids in beetle-killed wood could have a negative effect on pulping and aquatic ecosystems (Chow and Shepard 1996; Woo et al. 2005), it might help increase the dry and wet bonding strength for beetle-wood plywood. In addition, with the beetle-wood veneer, the glue might penetrate into the cell wall easier than the control veneer due to the less hemicellulose/lignin, resulting in even stronger bonding and reinforcement to the cell walls.

The reasons why the percent wood failure was higher with the beetle-wood veneer than the control veneer could be twofold: 1) the chemical components of the beetle-wood veneer were different from those of the control veneer; and 2) the green veneer sorting of the beetle-wood veneer was more accurate than that of the control veneer (Wang and Dai 2004). Although veneer over-drying could easily occur with the beetle-wood veneer, in the mill drying conditions, there could be more veneer being overdried with the control veneer than with the beetle-wood veneer due to the larger within-sort MC variation of the control veneer.

In summary, based on vacuum pressure tests, the shear strength of 5-ply plywood made from the beetle-wood veneer was consistently higher than that made from the control veneer. As well, average percent wood failure of plywood made from the beetle-wood veneer was about 10% and 27% higher than that made from the control veneer from both vacuum pressure and boiling dry boiling tests, respectively. For both tests, the average percent wood failure of plywood panels made from the beetle-wood veneer exceeded the 80% standard requirements under various gluing and lay-up conditions. In contrast, the average percent wood failure of plywood panels made from the control veneer did not meet the standard requirements. The results demonstrated that the wet bonding strength of the beetle-wood veneer is also higher than that of the control veneer. To achieve optimum bonding performance for beetle-wood plywood, assembly time should be cut down to about 10-15 min. and veneer temperature should be minimized when using the same glue spread level at 159 g/m^2 per single glue line as normally used by the control plywood.

5.1.3 The Effect of Mountain Pine Beetle Veneer on Plywood/LVL Hot-Pressing Process and Panel Properties

All 5-ply plywood panels made based on Table 2 were tested for physical properties including thickness, specific gravity and moisture content (MC) and mechanical properties such as bending MOE and MOR.

Table 17 shows the comparison of pressing time needed for the innermost glueline to reach 110ºC between 5-ply beetle-wood plywood and control plywood under various combinations of manufacturing parameters. In most cases, the pressing time of beetle-wood plywood was longer than that of control plywood. On average, compared to control plywood, the pressing time of beetle-wood plywood was about 7.6% or 9.6% longer for the innermost glueline temperature to reach 100°C and 110°C, respectively. The t-tests showed that the difference in the pressing time between 5-ply beetle-wood plywood and control plywood is significant at the $p = 0.05$ level. In addition, the gas pressure in the core during pressing of 5-ply beetle-wood plywood and control plywood was very low, with a range from 1 to 5 psi (0.007 to 0.034 MPa). There was no observed difference in maximum gas pressure between 5-ply beetle-wood plywood and control plywood. The results demonstrate that higher transverse air permeability in the beetle-wood veneer did not apparently contribute faster heat transfer, and in turn the shorter pressing time, since heat conduction, rather than heat convection, is generally the dominant transfer mechanism during pressing of veneer-based products (Wang et al. 2006). The reason why hot pressing time of 5-ply MPB plywood is longer than that of 5-ply control plywood is probably due to the fact that the MPB veneer is denser than the control veneer; in this case, more mass needs to be heated up. The implication is that when

manufacturing 5-ply beetle-wood plywood, about 25 seconds of hot pressing time needs to be added compared to the control plywood.

Table 17: Results of hot-pressing time for 5-ply beetle-wood plywood and control plywood (target temperature 100°C)

Experiment no.	Glue spread	Veneer temperature	Assembly time	Pressing time for innermost glueline to reach 100°C (seconds)							
	X_1	X_2	X_3	5-ply MPB plywood				5-ply control plywood			
	g/m^2 ($lb/1000ft^2$)	°C (°F)	(min)	Panel 1	Panel 2	Panel 3	Average	Panel 1	Panel 2	Panel 3	Average
1	159 (32.0)	21.1 (70)	10.0	280	280	278	279.3	240	220	235	231.7
2	159 (32.0)	32.2 (90)	15.0	240	200	225	221. 7	205	180	205	196. 7
3	159 (32.0)	43.3 (110)	20.0	235	235	200	223.3	200	210	215	208.3
4	174 (35.0)	21.1 (70)	15.0	260	240	240	246.7	205	250	225	226.7
5	174 (35.0)	32.2 (90)	20.0	230	205	210	215.0	240	225	220	228.3
6	174 (35.0)	43.3 (110)	10.0	220	200	210	210.0	200	200	200	200.0
7	189 (38.0)	21.1 (70)	20.0	245	255	260	253.3	250	235	240	241.7
8	189 (38.0)	32.2 (90)	10.0	220	260	220	233.3	200	200	205	201.7
9	189 (38.0)	43.3 (110)	15.0	225	240	205	223.3	205	235	225	221.7
Average				239.4	235.0	227.6	234.0	216.1	217.2	218.9	217.4

Table 18: Results of hot-pressing time for 5-ply beetle-wood plywood and control plywood (target temperature 110°C)

Experiment no.	Glue spread	Veneer temperature	Assembly time	Pressing time for innermost glueline to reach 110°C (seconds)							
	X_1	X_2	X_3	5-ply MPB plywood				5-ply control plywood			
	g/m^2 ($lb/1000ft^2$)	°C (°F)	(min)	Panel 1	Panel 2	Panel 3	Average	Panel 1	Panel 2	Panel 3	Average
1	159 (32.0)	21.1 (70)	10.0	342	340	343	341.7	305	265	280	283.3
2	159 (32.0)	32.2 (90)	15.0	295	280	280	285.0	255	230	270	251.7
3	159 (32.0)	43.3 (110)	20.0	318	295	255	289.3	250	260	270	260.0
4	174 (35.0)	21.1 (70)	15.0	315	300	315	310.0	250	300	280	276.7
5	174 (35.0)	32.2 (90)	20.0	278	280	265	274.3	295	278	275	282.7
6	174 (35.0)	43.3 (110)	10.0	260	260	265	261.7	248	245	255	249.3
7	189 (38.0)	21.1 (70)	20.0	315	310	350	325.0	295	280	310	295.0
8	189 (38.0)	32.2 (90)	10.0	300	300	280	293.3	270	240	260	256.7
9	189 (38.0)	43.3 (110)	15.0	278	295	265	279.3	260	280	275	271.7
Average				300.1	295.6	290.9	295.5	269.8	264.2	275.0	269.7

Table 19: Comparison of hot pressing time of 5-ply beetle-wood plywood and control plywood

Comparison of pressing time (seconds)	Pressing time to 100°C		Pressing time to 110°C	
	MPB	Control	MPB	Control
Mean	234.0	217.4	295.5	269.7
Variance	488.3	259.8	652.4	256.3
Observations	9	9	9	9
Hypothesized Mean Difference	0	$\lvert t \rvert > t_{critical}$	0	$\lvert t \rvert > t_{critical}$
df	8		8	
t Stat	2.84		4.01	
P(T<=t) one-tail	0.011		0.0020	
t Critical one-tail	1.86		1.86	
P(T<=t) two-tail	0.022		0.0039	
t Critical two-tail	2.31		2.31	

Table 20 shows the comparison of physical properties between the beetle-wood plywood and control plywood. The beetle-wood plywood was relatively thicker, heavier and lower in final MC compared to the control plywood. The average compression ratio (CR) was 7.2% for 5-ply beetle-wood plywood and 7.5% for control plywood using a platen pressure of 1.21 MPa (175 psi).

Table 21 shows the comparison of mechanical properties between the beetle-wood plywood and control plywood. The t-tests demonstrated that the MOE and MOR of the beetle-wood plywood were statistically higher by about 20% than those of the control plywood at the $p = 0.05$ level. Recall that from the veneer stress wave testing, the MOE of the beetle-wood veneer was only about 7.9% higher than that of the control veneer. The reason for this discrepancy could be due to the fact that the beetle-wood veneer had lots of cracks and splits which would be repaired and even strengthened during panel gluing and hot-pressing. The implication is that the beetle-wood veneer can be specially used for plywood applications requiring high stiffness and loading capacity such as flooring, decking and concrete forming.

Table 20: Comparison of physical properties of 5-ply beetle-wood plywood and control plywood

Experiment no.	Glue spread	Veneer temperature	Assembly time	Panel thickness		Panel specific gravity (SG)		Panel MC	
	X_1	X_2	X_3	MPB	Control	MPB	Control	MPB	Control
	g/m^2 ($lb/1000ft^2$)	°C (°F)	(min)	(mm)				(%)	
1	159 (32.0)	21.1 (70)	10.0	14.9	15.0	0.476	0.451	7.1	7.3
2	159 (32.0)	32.2 (90)	15.0	15.3	15.1	0.452	0.429	6.8	7.5
3	159 (32.0)	43.3 (110)	20.0	15.0	15.1	0.484	0.419	7.2	7.6
4	174 (35.0)	21.1 (70)	15.0	15.1	14.7	0.477	0.408	7.6	7.8
5	174 (35.0)	32.2 (90)	20.0	14.9	14.9	0.478	0.405	7.4	7.9
6	174 (35.0)	43.3 (110)	10.0	15.0	15.2	0.470	0.414	7.7	7.9
7	189 (38.0)	21.1 (70)	20.0	14.8	15.0	0.470	0.421	7.8	7.9
8	189 (38.0)	32.2 (90)	10.0	15.0	14.5	0.488	0.399	7.8	8.3
9	189 (38.0)	43.3 (110)	15.0	15.3	15.2	0.494	0.409	7.6	8.2
Average				15.04	14.98	0.477	0.417	7.4	7.8

Table 21: Comparison of mechanical properties of 5-ply beetle-wood plywood and control plywood

Experiment no.	Glue spread	Veneer temperature	Assembly time	Plywood panel MOE* parallel to face grain		Plywood panel MOR* parallel to face grain	
	X_1	X_2	X_3	MPB	Control	MPB	Control
	g/ m^2 (lb/1000ft^2)	°C (°F)	(min)	GPa (MMpsi)		MPa (psi)	
1	159 (32.0)	21.1 (70)	10.0	8.31 (1.21)	6.70 (0.98)	69.6 (10101)	47.6 (6908)
2	159 (32.0)	32.2 (90)	15.0	6.78 (0.98)	7.18 (1.04)	44.4 (6435)	57.6 (8350)
3	159 (32.0)	43.3 (110)	20.0	8.20 (1.19)	6.96 (1.01)	54.2 (7857)	55.2 (8000)
4	174 (35.0)	21.1 (70)	15.0	8.58 (1.24)	6.80 (0.99)	68.1 (9876)	52.1 (7556)
5	174 (35.0)	32.2 (90)	20.0	7.77 (1.13)	6.43 (0.93)	55.3 (8028)	47.5 (6888)
6	174 (35.0)	43.3 (110)	10.0	7.79 (1.13)	6.06 (0.88)	54.5 (7911)	38.8 (5628)
7	189 (38.0)	21.1 (70)	20.0	7.69 (1.12)	6.72 (0.97)	62.7 (9096)	47.9 (6950)
8	189 (38.0)	32.2 (90)	10.0	7.87 (1.14)	6.31 (0.92)	53.5 (7758)	39.9 (5787)
9	189 (38.0)	43.3 (110)	15.0	8.10 (1.17)	6.36 (0.92)	53.5 (7754)	44.7 (6482)
Average				7.90 (1.15)	6.62 (0.96)	57.3 (8313)	47.9 (6949)

Note: * a span (15 -inch) to depth (5/8 -inch) ratio of 24 was used. Conversion is needed to compare the values of MOE and MOR between different testing standards.

As described in Table 3, twelve 5-ply beetle-wood plywood panels were made using different combinations of glue spread, platen pressure and assembly time with three replicates. During plywood shear tests, one out of the three beetle-wood plywood panels had either glueline dryout or very rough veneer surface. Although the shear strength was largely unaffected, the percent wood failure of shear specimens was very low. The reason could be the over-drying of the beetle-wood veneer. Tables 22 and 23 summarize the results of shear strength and percent wood failure of 5-ply beetle-wood plywood made from normal dry veneer and overdried veneer, respectively, after receiving vacuum pressure and boiling-dry-boiling treatments. The results showed that with the normal dry beetle-wood veneer, No.1 experiment with 159 g/m^2 glue spread, 10 min. assembly time and 1.21 MPa platen pressure generated acceptable shear strength and percent wood failure; No. 3 experiment with 174 g/m^2 glue spread, 10 min. assembly time and 1.38 MPa platen pressure resulted in higher shear strength and percent wood failure. However, with the overdried beetle-wood veneer, the percent wood failure of experiment No. 1 and No. 3 failed to meet 80% wood failure requirements. Veneer over-drying makes veneer brittle, easy to split and more difficult to handle. Over-drying would also cause surface inactivation, poor glue transfer and penetration, leading in turn to panel delamination. Since the beetle-wood veneer is lower in MC compared to the control veneer, developing optimum drying schedules could be essential to reduce veneer breakage and overdrying, in turn to increase material recovery and panel quality. By comparing experiments No.1, No. 2

and No. 4, it seemed that for beetle-wood plywood, lower glue spread at 159 g/m^2 required corresponding shorter assembly time (< 15 min.) for quality gluebond, probably due to the faster glue penetration in the beetle-wood veneer.

Table 22: Shear strength and percent wood failure of 5-ply MPB plywood made from normal dry veneer

Experiment no.	With normal dry MPB veneer			Vacuum pressure		Boiling dry boiling	
	Glue spread	Assembly time	Platen pressure	Shear strength	Wood failure	Shear strength	Wood failure
	g/m^2 (lb/1000ft^2)	(min.)	MPa (psi)	MPa (psi)	(%)	MPa (psi)	(%)
1	159 (32)	10	1.21 (175)	1.06 (153.5)	81.4	0.97 (140.5)	87.9
2	159 (32)	15	1.38 (200)	0.88 (128.0)	75.3	0.85 (122.5)	72.0
3	174 (35)	10	1.38 (200)	0.97 (141.0)	98.0	0.94 (136.5)	97.0
4	174 (35)	15	1.21 (175)	0.77 (111.0)	89.3	0.78 (113.5)	95.5

Table 23: Shear strength and percent wood failure of 5-ply mountain pine beetle plywood made from overdried veneer

Experiment no.	With overdried MPB veneer			Vacuum pressure		Boiling dry boiling	
	Glue spread	Assembly time	Platen pressure	Shear strength	Wood failure	Shear strength	Wood failure
	g/m^2 (lb/1000ft^2)	(min.)	MPa (psi)	MPa (psi)	(%)	MPa (psi)	(%)
1	159 (32)	10	1.21 (175)	1.02 (148.3)	43.3	0.95 (137.9)	29.4
2	159 (32)	15	1.38 (200)	1.06 (153.0)	55.0	0.89 (129.5)	76.5
3	174 (35)	10	1.38 (200)	0.83 (120.1)	37.4	0.83 (120.3)	28.2
4	174 (35)	15	1.21 (175)	1.01 (146.3)	62.0	0.94 (136.8)	47.0

Table 24 summarizes the physical properties and two types of shear strength for the four 13-ply LVL panels, each made from the beetle-wood veneer and control veneer, respectively. By comparison, there seemed to be no significant difference in the pressing time between 13-ply beetle-wood LVL and control LVL, although beetle-wood LVL took slightly longer for the core to reach 105°C, the target temperature. Further work is needed to clarify whether there is a significant difference in the pressing time. However, under the same manufacturing conditions, compared to control LVL, beetle-wood LVL had smaller compression ratio (CR), lower moisture content (MC), higher specific gravity (SG) and higher shear strength in both parallel to grain and through-the-thickness.

Table 24: Comparison of physical properties and shear strength between 13-ply beetle-wood LVL and control LVL

13-ply LVL	Lay-up thickness	Pressing time	Panel thickness	Panel CR	Panel SG	Panel MC	Shear strength parallel to grain		Shear strength through-the-thickness
	mm (inches)	(min)	mm (inches)	(%)		(%)	MPa (psi)	WF (%)	MPa (psi)
MPB1	41.3 (1.626)	22.0	37.7 (1.484)	8.8	0.497	6.8	5.7 (829)	99	6.6 (954)
MPB2	41.5 (1.635)	20.7	36.7 (1.446)	11.5	0.500	6.7	5.7 (824)	100	7.8 (1137)
MPB3	41.6 (1.637)	19.3	37.1 (1.460)	10.8	0.480	6.9	5.2 (758)	100	7.5 (1090)
MPB4	42.5 (1.675)	24.0	38.5 (1.515)	9.5	0.507	6.4	5.2 (757)	98	7.7 (1109)
Average	41.7 (1.643)	21.5	37.5 (1.476)	10.1	0.496	6.7	5.5 (792)	99	7.4 (1072)
Control1	42.6 (1.679)	20.3	35.6 (1.401)	16.5	0.438	7.7	5.0 (720)	100	6.2 (896)
Control2	43.0 (1.692)	21.0	37.0 (1.455)	14.0	0.433	7.7	4.9 (716)	97	7.2 (1042)
Control3	42.5 (1.674)	22.7	37.8 (1.488)	11.1	0.467	7.0	5.0 (724)	100	6.8 (991)
Control4	42.7 (1.682)	21.0	37.5 (1.478)	12.2	0.455	7.1	5.0 (726)	100	6.5 (946)
Average	42.7 (1.682)	21.3	37.0 (1.455)	13.5	0.448	7.4	5.0 (721)	99	6.7 (969)

Table 25 summarizes flatwise and edgewise bending properties of the four 13-ply LVL panels made from the beetle-wood veneer and control veneer, respectively. By comparison, under the same manufacturing conditions, there was a significant difference in both edgewise and flatwise bending MOE and MOR, between beetle-wood LVL and control LVL, based on the 16 bending specimens cut from the four panels. On average, as far as LVL flatwise bending was concerned, the MOE and MOR of beetle-wood LVL were 11.5% and 18.2% higher than those of control LVL, respectively. Similarly, as far as LVL edgewise bending was concerned, the MOE and MOR of beetle-wood LVL were 13.7% and 21.7% higher than those of control LVL, respectively. The results also indicated that both average edgewise MOE and flatwise MOE of the beetle-wood LVL exceeded the 1.8E (1.8 million psi or 12.4 GPa) market requirements for both average and minimum MOE. As a result, the beetle-wood veneer could be well suited for making 1.8E or even higher grade LVL.

Table 25: Comparison of bending MOE and MOR between 13-ply beetle-wood LVL and control LVL

13-ply LVL	LVL flatwise bending				LVL edgewise bending			
	MOR		MOE		MOR		MOE	
	(MPa)	(psi)	(GPa)	(MMpsi)	(MPa)	(psi)	(GPa)	(MMpsi)
MPB1	68.1	9882	11.9	1.73	67.2	9753	12.3	1.78
MPB2	75.8	10992	13.7	1.98	80.8	11728	13.6	1.98
MPB3	53.2	7720	11.8	1.70	65.5	9501	12.3	1.78
MPB4	72.8	10553	13.0	1.89	68.8	9977	12.2	1.77
Average	67.5	9787	12.6	1.83	70.6	10240	12.6	1.83
Control1	56.2	8147	11.5	1.67	60.1	8717	12.4	1.80
Control2	50.5	7331	10.3	1.49	56.3	8172	11.3	1.64
Control3	64.1	9301	11.9	1.73	61.2	8874	10.1	1.46
Control4	57.6	8351	11.6	1.68	54.4	7892	10.8	1.56
Average	57.1	8283	11.3	1.64	58.0	8413	11.1	1.61

In summary, the pilot plant tests of 5-ply beetle-wood plywood and 13-ply LVL demonstrated that beetle-wood plywood/LVL had smaller compression ratio (relatively thicker), heavier (higher specific gravity) and lower final MC compared to control plywood and LVL. Beetle-wood plywood required longer pressing time than control plywood, indicating that the current pressing schedules used for the control plywood need to be adjusted. However, beetle-wood plywood had about 20% higher MOE and MOR than control plywood. Similarly, beetle-wood LVL had about 12.5% higher bending MOE and 20.0% higher bending MOR than control LVL. Further, beetle-wood LVL had higher shear strength in both parallel-to-grain and through-the-thickness. As a result, the beetle-wood veneer could be well suitable for making 1.8 E grade LVL (1.8 million psi or 12.4 GPa). With veneer stress grading, a portion of the beetle-wood veneer could be further extracted for making 2.0 E grade LVL (2.0 million psi or 13.8 GPa). To maximize the value recovery from this beetle-killed resource, it is recommended that: 1) MOE-based stress grading be used to maximize the grade outturns; and 2) the stress graded MPB veneer be used for structural LVL and plywood applications requiring higher stiffness and loading capacity such as I-joists, flanges, flooring, decking and concrete forming.

Aside from the narrower clipping width, more accurate moisture sorting and higher drying productivity identified previously (Wang and Dai 2004), segregating beetle-wood logs also provides an opportunity to manufacture higher stiffness plywood/LVL products with superior dry and wet bonding quality. This could further offset the reduction in material recovery and some appearance-based plywood products in the specialty market.

5.2 Mill Trial

5.2.1. Veneer Drying, Stress Grading and Visual Grading

Our previous study demonstrated that the beetle-wood veneer required shorter drying time, and the visual grading system needed to be upgraded for identification of defects within the blue-stained area (Wang and Dai 2004). To effectively tackle the beetle-wood veneer, this collaborating mill has recently installed an upgraded Raute Mecano VDA/DMA/2004 Grader, which is able to differentiate physical defects from the blue stain.

As shown in Figure 19, the frequent distribution of ultrasonic propagation time (UPT) was established for the population of both beetle-wood veneer and control veneer. The average UPT was 413.7 μs for the beetle-wood veneer compared to 402.1 μs for the control veneer. Similarly, as shown in Figure 20, the frequent distribution of veneer density was established for the population of both beetle-wood veneer and control veneer. The average density was 0.424 g/cm^3 for the beetle-wood veneer compared to 0.392 g/cm^3 for the control veneer. Further, as shown in Figure 21, the frequent distribution of veneer MOE was established and compared between the beetle-wood veneer and control veneer population. Compared to the control veneer (11170 MPa or 1.62 MMpsi), the beetle-wood veneer (12480 MPa or 1.81 MMpsi) was about 11.7% higher in the average MOE. The results confirmed that the beetle-wood veneer had longer UPT, higher density and MOE compared to the control veneer. Pilot plant results demonstrated that on average, the beetle-wood veneer was about 7.9% higher in MOE than the control veneer.

As far as grade outturns are concerned, based on Figure 21, it is estimated that the beetle-wood veneer could generate about 20% more high-grade veneer for structural grade LVL and specialty plywood products. Currently, this mill consumes 400,000 m^3 logs annually, among which about 10% of total log volume are beetle-wood logs. Based on the previous study, the overall recovery for beetle-wood logs is about 42.4% (Wang and Dai 2004). The price gap between LVL and regular sheathing grade plywood is estimated at $500-800/m^3. As a result, this 20% more high-grade outturn can translate into more than $1.5 million additional savings annually for this mill. Further work is needed to optimize the stress grading of the beetle-wood veneer for higher stiffness LVL/plywood manufacture to maximize the value recovery from this resource.

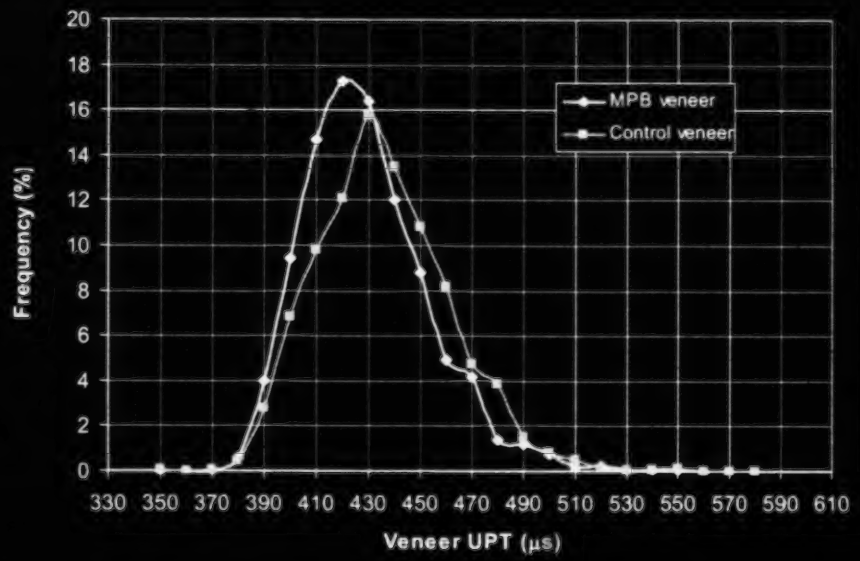


Figure 19: The comparison of UPT distribution between the beetle-wood veneer and control veneer

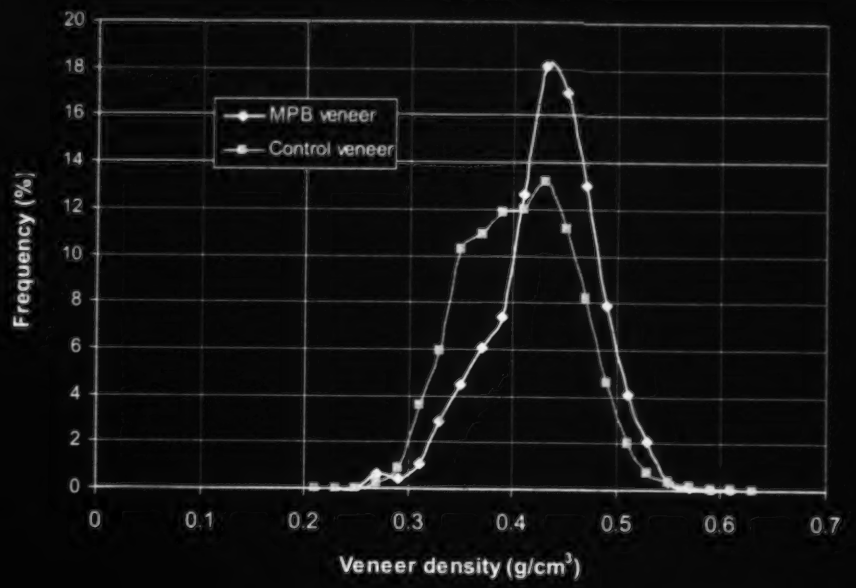


Figure 20: The comparison of density distribution between the beetle-wood veneer and control veneer

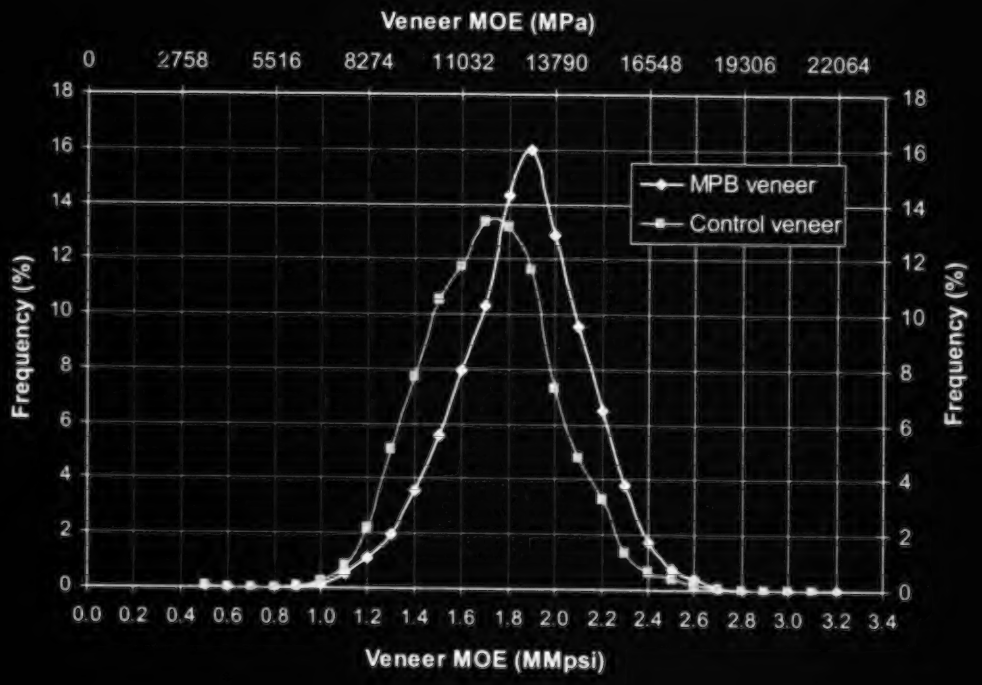


Figure 21: The comparison of MOE distribution between the beetle-wood veneer and control veneer

5.2.2. *Panel Gluing, Lay-up and Pressing*

Figure 22 shows the glue coverage captured by the camera at the mill glue station. Although glue application was performed reasonably well, glue skips did exist. In addition to the glue spread level, veneer roughness and thick and thin were found to be the other two key variables affecting glue coverage. To increase the panel gluebond performance and reduce panel delamination, veneer thickness and roughness control and real-time monitoring of glue coverage were deemed to be important.

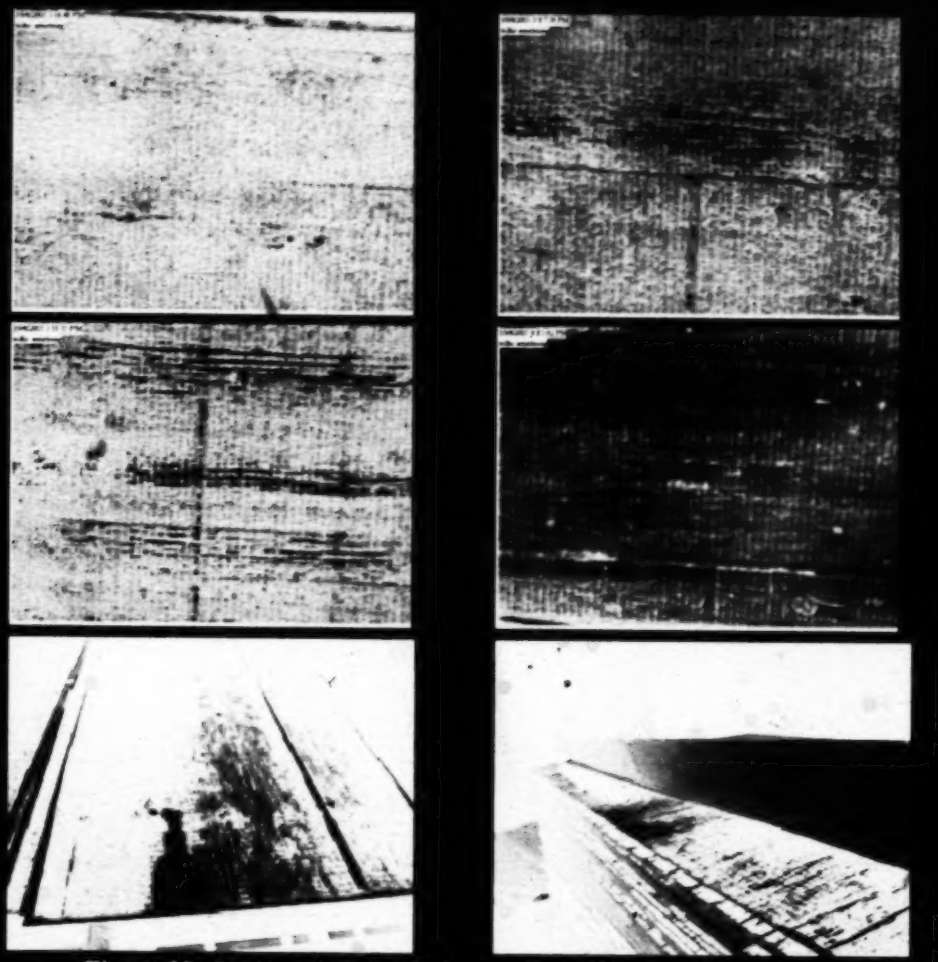


Figure 22: Various degrees of glue coverage after spreading

As shown in Table 26, the veneer temperature, lay-up time, open assembly time, closed time and standing time and total assembly time were tabulated for both 5-ply control plywood and beetle-wood plywood. Although efforts were made to control the total assembly time from 10 to 15 min., the actual total assembly time for 5-ply beetle-wood plywood (12.5 - 19.5 min.) was longer than that for 5-ply control plywood (11.0 - 12.5 min.) due to additional time for adjustment of glue spread level and pressing schedules. The ambient temperature during the mill trial was 19.4°C (or 67°F), and platen temperature was 140.5°C or 285°F. Platen pressure was 206 to 223 psi (1.42 to 1.54 MPa) for the press 1 and 193 to 208 psi (1.33 to 1.43 MPa) for the press 2. The target innermost glueline temperature was 112°C upon unloading the press.

Table 26: The veneer temperature and total assembly time for 5-ply beetle-wood plywood and control plywood

5-ply plywood		Glue spread* g/m^2 ($lb/1000ft^2$)	Pressing time (sec.)	Veneer temp. °C (°F)	Lay-up time (sec.)	Open assembly time (sec.)	Closed time (sec.)	Standing time (sec.)	Total assembly time (sec.)
Control 1	Press 2	144 (29.0)	255	21 (70)	120	120	180	240	660
Control 2	Press 2	149 (30.0)	255	22 (71)	180	120	180	210	690
Control 3	Press 2	154 (31.0)	255	21 (70)	210	120	180	240	750
Control 4	Press 2	159 (32.0)	255	21 (69)	165	120	180	225	690
Average		152 (30.5)	255	21 (70)	169	120	180	229	698
MPB 1	Press 1	144 (29.0)	285	22 (72)	225	40	180	502	947
	Press 2				200	120	180	300	800
MPB 2	Press 1	144 (29.0)	255	22 (72)	140	40	180	575	935
	Press 2				120	120	180	340	760
MPB 3	Press 1	152 (30.5)	285	24 (75)	165	180	180	620	1145
	Press 2				160	240	180	420	1000
MPB 4	Press 1	152 (30.5)	255	24 (75)	155	180	180	650	1165
	Press 2				130	270	180	535	1115
MPB 5	Press 1	159 (32.0)	285	25 (77)	150	40	180	585	955
	Press 2				145	120	180	375	820
MPB 6	Press 1	159 (32.0)	255	25 (77)	160	40	180	525	905
	Press 2				140	120	180	450	890
Average		152 (30.5)	270	24 (75)	158	126	180	490	953

Note: *per single glueline

As shown in Table 27, based on pressing time for the innermost glueline to reach 100°C, there existed no significant difference in the pressing time between 5-ply control plywood and beetle-wood plywood. When pressing time was 255 sec., the innermost glueline temperature was almost identical for control plywood (107.2°C) and beetle-wood plywood (107.8°C), which was still below the target 112°C. This result seemed to contradict that obtained from the pilot plant test in which beetle-wood plywood required about 7.5%-10.0% longer pressing time than control plywood. The main reason could due to the fact that: 1) the temperature of the beetle-wood veneer (24°C) was higher than that of the control veneer (21°C); 2) the thermocouple location was near the edge of the panel; or 3) there existed random veneer density variation. It is anticipated that the temperature rise near the edge of the panel is faster than that at the panel centre. For beetle-wood plywood, when pressing time increased to 285 sec., the average innermost glueline temperature was about 111°C, close to the target 112°C.

Table 27: The pressing time and final innermost glueline temperature for 5-ply beetle-wood plywood and control plywood

5-ply plywood	Pressing time for innermost glueline to reach 100 °C (sec.)				Total pressing time (sec.)	Final temperature of innermost glueline for Press 1 and/or Press 2 °F (°C)			
Control 1	225				255	222 (105.6)*			
Control 2	215				255	222 (105.6)*			
Control 3	210				255	230 (110.0)*			
Control 4	Missed				255	Missed			
Average	216				255	225 (107.2)*			
	Press 1		Press 2			Press 1		Press 2	
MPB 1	225	220	210	200	285	228 (108.9)	234 (112.2)	235 (112.8)	237 (113.9)
MPB 2	240	205	220	215	255	219 (103.9)	227 (108.3)	222 (105.6)	222 (105.6)
MPB 3	190	200	210	198	285	234 (112.2)	236 (113.3)	230 (110.0)	231 (110.6)
MPB 4	218	206	195	190	255	222 (105.6)	229 (109.4)	228 (108.9)	229 (109.4)
MPB 5	210	220	195	215	285	234 (112.2)	224 (106.7)	229 (109.4)	231 (110.6)
MPB 6	195	205	195	225	255	230 (110.0)	230 (110.0)	234 (112.2)	220 (104.4)
Average	211		206		255	226 (107.8)		226 (107.8)	
					285	232 (111.0)		232 (111.0)	

Note: *the readings were taken from press 2 only.

5.2.3. Panel Gluebond Performance and Stiffness

As part of mill plywood quality control, the CertiWood (formerly Canply) and the primary glue supplier Dynea routinely check the gluebond performance for this mill. For 5-ply control plywood, the mill history data from 2004 to now showed that with a glue spread level from 144.0 to 159.0 g/m^2 (29.0 to 32 lb/1000 ft^2) per single glueline, the average percent wood failure was quite steady with 85.3% - 89.1% from vacuum pressure tests and 89.3% from boiling-dry-boiling tests.

Table 28 summarizes the gluebond performance testing results from Dynea and Forintek for both beetle-wood plywood and control plywood. For the seven control plywood panels sampled, the average percent wood failure was 74.1% from Dynea and 71.6% from Forintek. These readings were somewhat below the target (80%). Besides the effect of veneer roughness and dryout, the relatively shorter pressing time used in the mill could be the main factor. For beetle-wood plywood panels, both glue spread and pressing time had effect on percent wood failure.

Table 28: The gluebond performance for 5-ply beetle-wood plywood and control plywood

5-ply plywood	Glue spread*	Pressing time (sec.)	Results from Dynea			Results from Forintek			
			Wood failure (%)	Shear strength		Wood failure (%)	Shear strength		Note****
				(psi)	(KPa)		(psi)	(KPa)	
Control 1	144 (29.0)	255**	55.0	0.79	5.4	77.0	1.42	9.8	
Control 2	149 (30.0)	255**	78.5	1.15	7.9	68.1	1.37	9.4	8.3% dryout
Control 3	154 (31.0)	255**	74.0	1.12	7.7	79.1	1.35	9.3	8.3% dryout
Control 4	159 (32.0)	255**	79.5	0.98	6.8	62.3	1.38	9.5	12.5% dryout
Average	152 (30.5)	255**	74.1	1.04	7.2	71.6	1.38	9.5	8.3% dryout
MPB 1	144 (29.0)	285	84.8	1.19	8.2	66.0	1.59	11.0	30.5% dryout 13.9% rough
MPB 2	144 (29.0)	255	72.9	0.95	6.5	77.7	1.23	8.5	14.8% dryout 9.3% rough
MPB 3	152 (30.5)	285	85.8	1.15	7.9	92.2	1.12	7.7	3.7% dryout 8.3% rough
MPB 4	152 (30.5)	255	77.8	1.02	7.0	72.6	1.16	8.0	37.0% dryout 8.3% rough
MPB 5	159 (32.0)	285	83.5	1.15	7.9	77.0	1.33	9.2	27.8% dryout 13.0% rough
MPB 6	159 (32.0)	255	80.5	1.03***	7.1	60.8	1.12	7.7	30.6% dryout 20.4% rough
Average	152 (30.5)	270	80.9	1.08	7.4	74.4	1.26	8.7	24.1% dryout 12.2% rough

Note: * per single glueline;

** pressing time used in the mill for control plywood;

*** one panel was undercured;

**** percent dryout and percent rough were determined based on the shear specimens tested.

The effect of glue spread and pressing time on 5-ply beetle-wood plywood was statistically analyzed using the testing results from Dynea (SAS Institute Inc. 1995). Table 29 summarizes the results from analysis of variance for the two-factor whole model. The model fitted the experimental data with 0.901 of R^2 (SEE = 0.047), which indicates that the model explained nearly 90.1% of the variation in the data.

Table 29: The analysis of variance for the gluebond p. . formance of 5-ply mountain pine beetle plywood

Source	Degree of freedom	Sum of squares	Mean square	F ratio
Model	3	0.0405	0.0135	6.08
Error	2	0.0044	0.0022	p = 0.144 (Prob>F)
Total	5	0.0449		

Figures 23 and 24 show the sensitivity of the glue spread level on gluebond performance for 5-ply mountain pine beetle plywood at pressing times of 255 sec. and 285 sec., respectively. In general, compared to the glue spread levels from 144.0 to 159.0 g/m^2 (29.0 to 32.0 lb/1000ft^2) per single glueline, the pressing time had more significant effect on plywood gluebond performance. When 255 sec. pressing time was used, the percent wood failure increased with glue spread level, but the average value still failed to achieve the 80% target. In comparison, when 285 sec. pressing time was used, the percent wood failure reached the minimum 80% target at the three different glue spread levels. For manufacturing 5-ply beetle-wood plywood, a glue spread level from 144.0 to 153.0 g/m^2 seemed to be sufficient. Note also from Table 28 that one beetle-wood plywood panel with a shorter pressing time (255 sec.) was undercured. As a result, as far as the gluebond performance was concerned, 5-ply beetle-wood plywood required a pressing time of 285 sec. compared to 255 sec. used for control plywood in the mill, which translates into an increase of pressing time by about 11.8%. Based on the pilot plant results for 5-ply beetle-wood plywood, an increase of pressing time by 9.6% was needed for the innermost glueline temperature to reach 110°C. Therefore, it was concluded that compared to 5-ply control plywood, the pressing time should be lengthened about 10% for manufacturing 5-ply beetle-wood plywood to achieve quality gluebond performance.

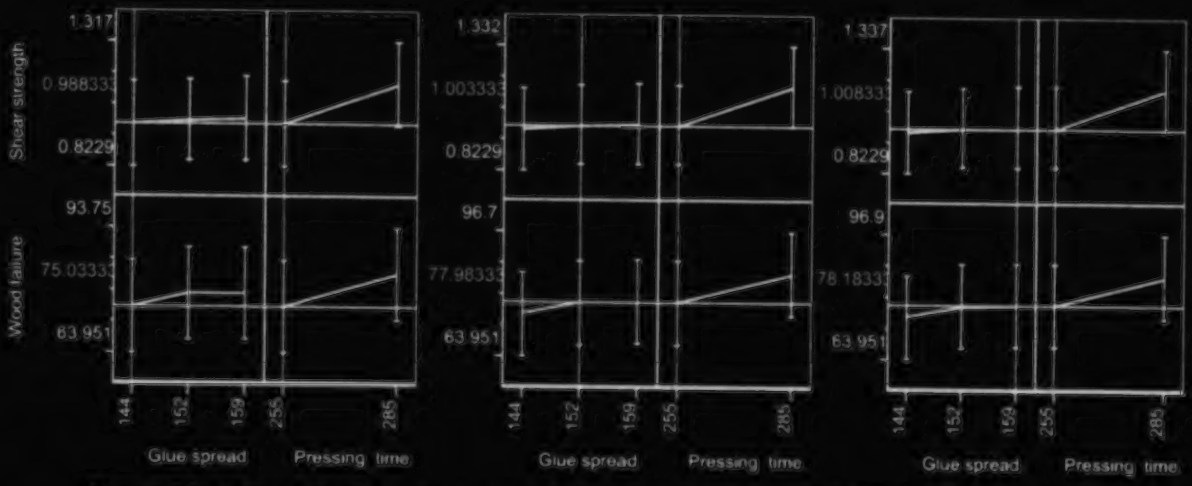


Figure 23: Sensitivity of glue spread on gluebond performance at 255 sec. pressing time

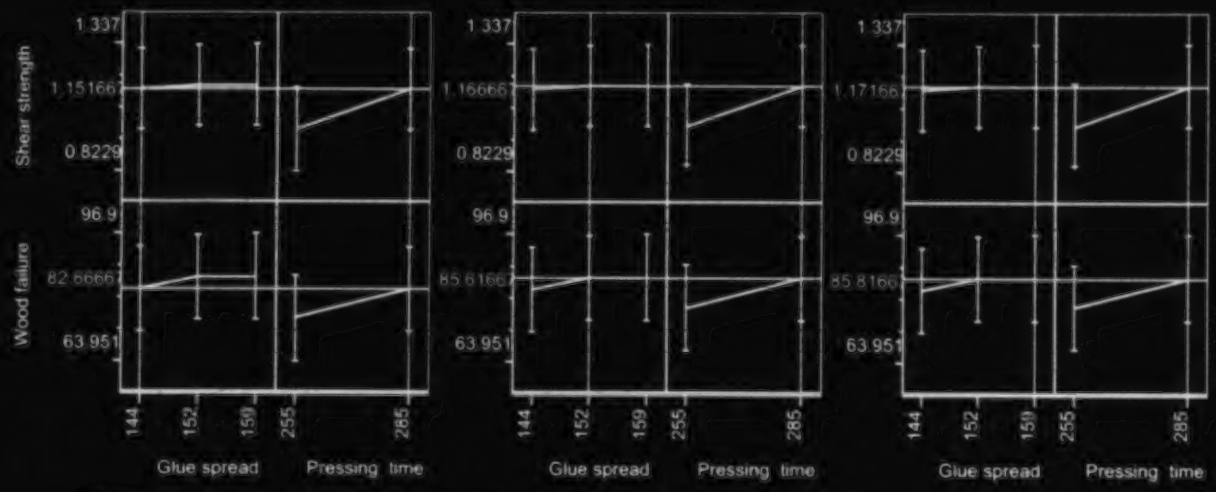


Figure 24: Sensitivity of glue spread on gluebond performance at 285 sec. pressing time

Due to the relatively longer assembly time used in the mill (12.5 - 19.5 min.), glue dryout became more significant with beetle-wood plywood compared to control plywood. As shown in Table 28, for each test run, of 108 shear specimens cut (12 pieces/panel x 9 panels) for vacuum pressure tests at Forintek, the average glue dryout rate of beetle-wood plywood was about 24.1% which was significantly higher than 8.3% with control plywood. Pilot plant results indicated that for the 5-ply beetle-wood plywood, the total assembly time should be within 10-15 min. with a shorter time yielding better gluebond performance.

Table 30 shows the testing results of bending MOE and MOR for 5-ply beetle-wood plywood and control plywood. Based on the t-tests, beetle-wood plywood was 13.5% and 22.5% higher in bending MOE and MOR, respectively, compared to control plywood. The results were in conformation with those from the pilot plant tests in which about 20% difference in MOE and MOR was identified. It is concluded that the plywood panels made from the beetle-wood veneer was significantly stronger than those made from the control veneer.

Table 30: The bending MOE and MOR for 5-ply beetle-wood plywood and control plywood

5-ply plywood	Glue spread*	Pressing time (sec.)	Plywood parallel bending performance***				
			MOE (MPa)	MOR (MPa)	MOE (MMpsi)	MOR (psi)	Calibrated MOE (MMpsi)
Control 1	144(29.0)	255**	5368.5	38.0	0.78	5515.5	1.25
Control 2	149(30.0)	255**	7897.3	50.6	1.15	7339.3	1.83
Control 3	154(31.0)	255**	5869.8	38.6	0.85	5594.3	1.36
Control 4	159(32.0)	255**	7532.5	53.8	1.09	7799.8	1.75
Average	152(30.5)	255**	6667.0	45.2	0.97	6562.0	1.55
MPB 1	144(29.0)	285	7523.2	53.8	1.09	7801.6	1.75
MPB 2	144(29.0)	255	7816.0	59.1	1.13	8568.4	1.81
MPB 3	152(30.5)	285	7882.1	53.9	1.14	7816.0	1.83
MPB 4	152(30.5)	255	7418.2	56.0	1.08	8118.9	1.72
MPB 5	159(32.0)	285	7418.2	58.6	1.08	8118.9	1.72
MPB 6	159(32.0)	255	7524.5	53.6	1.09	7778.2	1.75
Average	152(30.5)	270	7597.0	55.8	1.10	8034.0	1.76

Note: * per single glueline;

** mill pressing time for control plywood;

***a span (15-inch) to depth (5/8-inch) ratio of 24 was used. Conversion is needed to compare the values of MOE and MOR between different testing standards.

In summary, for manufacturing 5-ply beetle-wood plywood at the mill, the optimum gluing and pressing parameters are as follows: assembly time 10-15 min., glue spread level 144-152 g/m^2 per single glue line and pressing time 285 sec. while minimizing veneer temperature. Compared to the control veneer, the beetle-wood veneer is denser and stronger. Hence, it is well suitable for making specialty structural plywood products such as decking and concrete forming requiring higher stiffness and strength and better gluebond performance.

6 Conclusions

Based on the results from pilot plant tests and mill trials, this study found that the beetle-wood veneer is denser and stronger than the control veneer from typical white wood mix (i.e. white spruce, lodgepole pine and subalpine fir). As long as manufacturing parameters are properly adjusted in drying, grading, gluing and hot-pressing, segregating beetle-killed logs provides an opportunity to manufacture higher stiffness plywood/LVL products with superior dry and wet gluebond quality for such applications as wood I-joists, beams and headers, flooring, decking and concrete forming. This could offset to a large degree the reduction in material recovery and some appearance-based plywood products in the Japanese

market. As well, the practice of segregation will become important for recovering the highest value since the mountain pine beetle-killed wood will count for greater than 25% of total log supply in the mill with most of logs being grey stage materials.

The plywood production was affected by beetle-wood logs as follows:

- The beetle-wood veneer is lower in moisture content (MC), more brittle, and more difficult to handle. It also has various degrees of blue stain. The machine vision technology currently used by some plywood/LVL mills cannot differentiate the physical defects within the blue-stained area. To improve veneer visual grading, the existing vision systems can be upgraded to mask the effect of blue stain or to segregate the blue-stained veneer using a saturation color index. To increase material recovery and panel gluebond performance, veneer overdrying needs to be minimized.
- Transverse air permeability tests demonstrated that the panels made from the beetle-wood veneer are about 50%-70% more permeable than those made from the control lodgepole pine veneer. However, there seems to be no significant difference in terms of transverse air permeability between the beetle-wood veneer and the control veneer from the typical white wood mix. Veneer density has a significant impact on heat transfer during plywood hot-pressing.
- Lap-shear tests demonstrated that using loose-to-tight construction improves the panel shear strength for both beetle-wood veneer and control veneer or their combination. Compared to the control veneer, the beetle-wood veneer has a positive effect on the panel dry bonding strength. Five-ply plywood gluebond performance tests from the pilot plant tests and mill trials demonstrated that the beetle-wood veneer and control veneer display dramatic differences in gluing and wet bonding properties. Compared to the control veneer, the beetle-wood veneer is also better in panel wet bonding performance, measured by shear strength and percent wood failure. Further, beetle-wood plywood is easier to achieve 80% wood failure standard requirements. It is therefore believed that changes in beetle-wood plywood bondability are due to changes of surface chemistry of the beetle-wood veneer. It is further hypothesized that the glue may penetrate into the cell wall of the beetle-wood veneer much easier than in the control veneer due to less hemi-cellulose/lignin composition in the beetle-wood veneer, resulting in even stronger bonding and reinforcement to its cell walls. This could help explain why the hot-pressing time has a more significant effect on the percent wood failure than the glue spread levels. To achieve optimum gluebond performance and minimum manufacturing cost for beetle-wood plywood, glue spread can be kept at the same level as currently used by the control plywood. However, the pressing time should be lengthened by about 10% compared to that used by control plywood, and the assembly time should also be reduced to about 10 -15 min.
- Both pilot plant tests and mill trials demonstrated that the beetle-wood veneer is about 10% higher in average MOE and 20% higher in stress grade outturns compared to the control veneer, which can translate into more than $1.5 million additional savings for the mill annually when processing 10% of mountain pine beetle-killed logs. Five-ply plywood manufacturing tests from the pilot plant and mill trials demonstrated that the MOE and MOR of beetle-wood plywood are 13.5 -20.0% and 20.0 -22.5% higher than those of control plywood, respectively. Pilot plant preliminary tests further demonstrated that the bending MOE and MOR of 13-ply beetle-wood LVL are about 12.5% and 20.0% higher than those of 13-ply control LVL, respectively. As a result, the beetle-wood veneer is more suitable for making higher stiffness LVL and specialty structural plywood products. By implementing this product strategy, the value recovery from the beetle-killed resource can be dramatically increased.

The outcome of this study will help plywood industry maximize the value recovery from mountain pine beetle-attacked logs through increased productivity, material recovery and reduced manufacturing cost.

The results help reinforce the Mountain Pine Beetle Initiative Epidemic Risk Reduction & Value Capture R&D Strategy.

7 Recommendations

This study addressed an important issue facing 15 plywood/LVL mills in B.C. Unlike other panel industry, plywood mills generally do not segregate lodgepole pine logs from the white wood mix comprising white spruce, lodgepole pine and subalpine fir to manufacture standard CSP plywood.

The beetle-wood veneer sheets sampled from the trial mill were peeled from the typical mixture of beetle-killed logs at different stages of attack being processed by the mill. Currently in this mill, the beetle-killed logs accounted for about 10% of total logs procured with green stage being 85% and red stage being 15% in volume breakdown. In the near future, the beetle-wood logs will account for more than 25% of total mill supply with most of logs being grey stage materials. To extract the higher value from this beetle-killed resource, segregating beetle-wood logs from normal white wood mix will become extremely important. Since grey stage logs are generally very dry with an average MC less than fibre saturation point (FSP) and may contain serious cracks, sorting of beetle-wood logs at the woodlands or log yards for different panel products appears to be essential. In addition, finding an effective log conditioning (or rehydration) method is vital for increasing material recovery through improved veneer peeling.

To reduce veneer breakage and overdrying, and in turn to increase material recovery and panel gluebond quality, the issue of the beetle-wood veneer drying needs to be revisited. Developing optimum drying schedules for the beetle-wood veneer is essential. A more thorough study on glue penetration, glue dryout and bondability is also needed for the beetle-wood veneer to increase panel gluebond performance.

Compared to other wood composite products such as medium density fibreboard (MDF), oriented strand board (OSB), particleboard and sheathing-grade plywood, LVL and specialty structural plywood have the highest market price. To maximize the value recovery from this beetle-killed resource, a further study on beetle-wood LVL and specialty structural plywood should be conducted. To uplift grade outturns for higher stiffness LVL and plywood, MOE-based veneer stress grading is strongly recommended instead of ultrasonic propagation time (UPT)-based.

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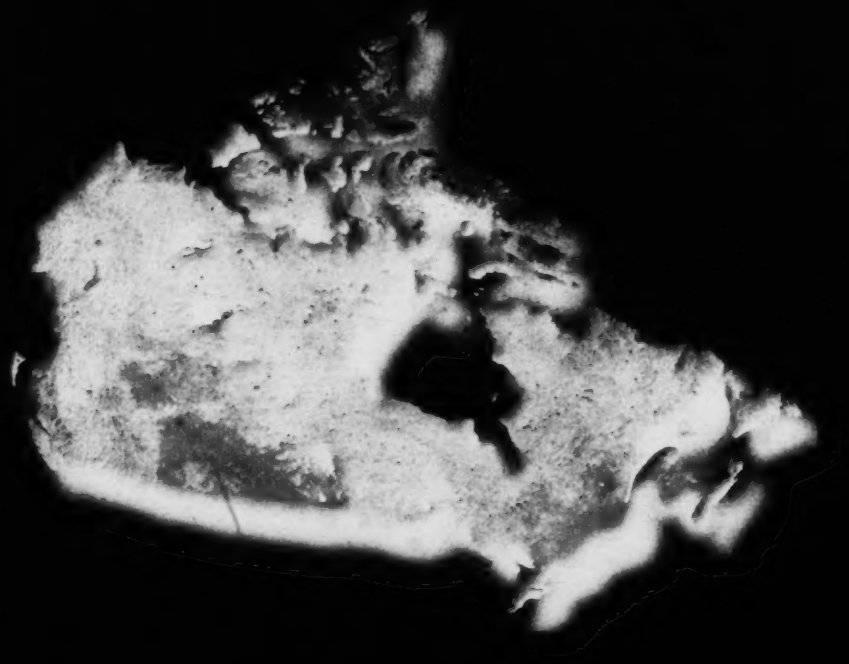

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